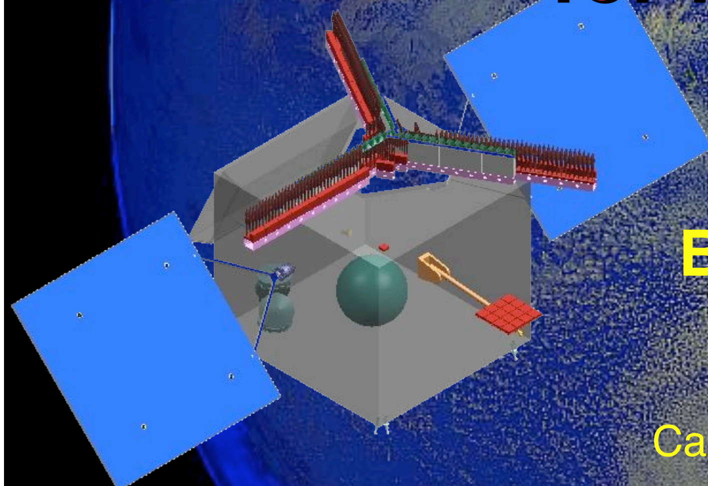
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

GeoSTAR

A Geosynchronous Microwave Sounder for NASA and NOAA



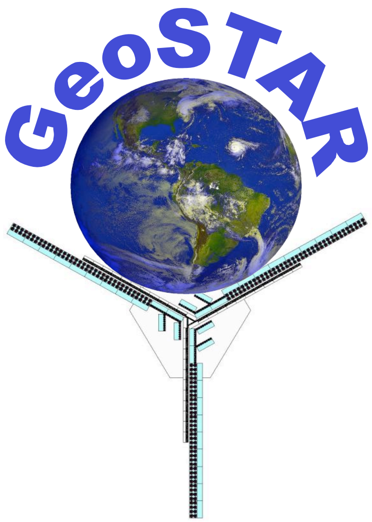
Bjorn Lambrigtsen

Jet Propulsion Laboratory
California Institute of Technology

JCSDA seminar

Camp Springs; September 26, 2008

Outline



1. Basis for MW in GEO
2. Infrared vs. microwave sounders
3. Science & applications
4. Algorithm development
5. Technology development
6. Mission development
7. GOES-R mission of opportunity

JPL

Summary

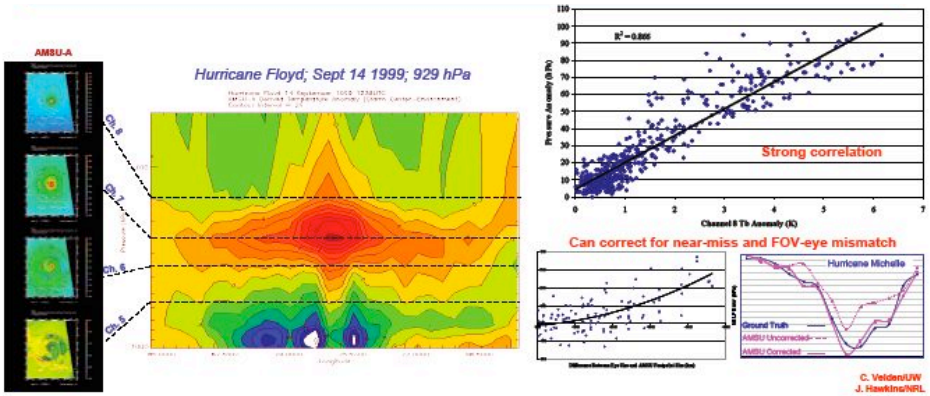
- **It is now feasible to implement a GEO/MW in the near future**
  - We must move quickly to take advantage of the current GOES-R/S opportunity
  - 4-year development: can be ready for 2014 launch
  - Risk is moderate: mature design & technology, many descope options & fallback solutions are available
- **Benefits: Brings LEO capabilities to GEO ⇒ "Geosynchronous AMSU"**
  - Primary focus on *hurricanes:* now-casting, rapid intensification, model & forecast improvements
  - Significant impact expected on both global and regional NWP - *no data gaps in cloudy scenes, storms*
  - Greatly-improved boundary layer, cloud and precipitation process *models;* climate variability; ENSO
  - Provides *advanced sounder* solution while waiting for HES
- **Instrument concept & technology developed by NASA, endorsed by NOAA**
  - Proven instrument concept meets measurement requirements and is ready for flight development
  - Flexible design with a number of descope options to match available resource allocations
  - Flexible architecture with a number of accommodation options to match available platform space
  - No moving parts; no interference with other payloads
- **NASA-NOAA teaming opportunity**
  - Urgent action required to use ex-HES slot for GeoSTAR as MoO on GOES-R or GOES-S
  - Unique opportunity to greatly enhance cloudy & hurricane remote sensing at low incremental cost
  - *Decisive action required!*
    - User community must speak up
    - NOAA must communicate with NASA
    - *"We need this!"*

GEO/MW Sounder Applications

- **Weather forecasting** -Improve regional forecasts; severe storms
  - All-weather soundings, including cloudy and stormy scenes
  - Full hemispheric soundings @<50/25 km every ~ 15-30 minutes (continuous)
  - "Synoptic" rapid-update soundings => Forecast error detection; 4DVAR applications
- **Hurricane diagnostics** -Quintessential hurricane sensor
  - Scattering signal from hurricanes/convection easily measurable
  - Measure *location*, *intensity* & vertical *structure* (incl. *shear*) of deep convection
  - Detect *intensification/weakening* in real time, frequently sampled (< 15 minutes)
  - Measure all three phases of water: vapor, liquid, ice - including rain/snow
  - Use for operational analysis & in research to improve microphysics of models
- **Rain** -Complements current capabilities
  - Full hemisphere @ ≤ 25 km every 15 minutes (continuous) - both can be improved
  - Directly measure storm and diurnal *total rainfall*: predict flooding events
  - Measure *snowfall*, light rain, intense convective precipitation
- **Tropospheric wind profiling** -NWP, transport applications
  - Surface to 300 mb; very high temp.res.; in & below clouds
  - Major forecast impact expected (OSSE planned) - particularly for hurricanes
  - Air quality applications (pollution transport)
- **Climate research** -Hydrology cycle, climate variability
  - Stable & continuous MW observations => Long term trends in T & q and storm stats
  - Fully resolved diurnal cycle: water vapor, clouds, convection
  - ENSO observer: Continuous observations from "warm pool" to Pacific coast under all conditions
  - "Science continuity": GeoSTAR channels = AMSU channels

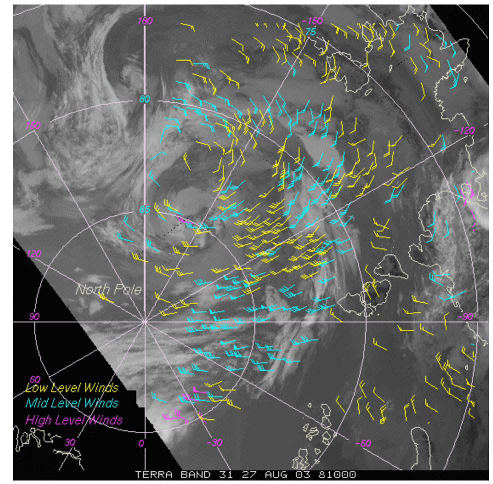
Measurement Highlights

Hurricane intensity (warm core anomaly)

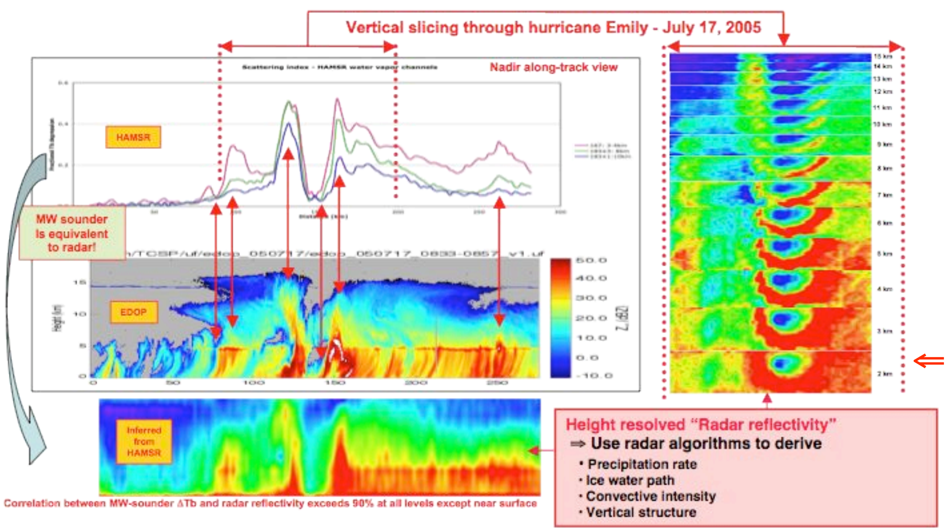


Tropospheric wind vectors (AMV)

- Current capabilities
  - LEO satellites: MODIS
    - Polar regions only
    - Limited-accuracy water vapor profiles
  - GEO satellites: IR sounder
    - Poor sampling: clear only
    - Uncertain height assignment
  - GEO satellites: IR/Vis imager
    - Cloud tracking: cloud tops only
- PATH capabilities
  - Clear AND cloudy
    - Including below clouds
  - Continuous: no time gaps
  - Applicable algorithms available
    - UW (Velden et al.)



"Radar reflectivity"



Height resolved "Radar reflectivity"
⇒ Use radar algorithms to derive
- Precipitation rate
- Ice water path
- Convective intensity
- Vertical structure

Precipitation

Example precipitation product derived from LEO/MW sounder (AMSU)

Red: light rain
Green: moderate
Blue: heavy

R. Bennartz

⇐ "Radar reflectivity" method most promising for precipitation

All of the above can be used in operational analysis of *intensity, size, location of convective center in 3 dimensions ⇒ assessment of vertical shear*

A GEO/MW Sounder Is Broadly Justified

NASA	Strategic Plan (2006)	Goal 3A	Study Earth from space to advance scientific understanding and meet societal needs
	Science Plan (2007)	Science questions	Variability: How are global precipitation, evaporation, and the cycling of water changing?
			Response: What are the effects of clouds and surface hydrologic processes on Earth's climate?
			Consequences: How are variations in local weather, precipitation, and water resources related to global climate variation ?
			Prediction: How can weather forecast duration and reliability be improved? (How will water cycle dynamics change in the future?)
		Missions	Weather FA: GeoSTAR: Geostationary synthetic aperture microwave radiometer
	Roadmaps (2005-06)	Weather F A	GEO Microwave sounding: Improved short-term forecasts
NOAA	Strategic Plan (2005)	Climate	Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship
		Weather	Increase lead time and accuracy for weather and water warnings and forecasts
			Improve predictability of the onset, duration, and impact of hazardous and severe weather and water events
			Increase development, application, and transition of advanced science and technology to operations and services
	Priorities	Observations	Capable and reliable observation infrastructure: Platform investments needed to meet high priority program requirements
		Forecasts	Forecast accuracy for high impact weather: Accurate short-term hurricane intensity forecasts
	NESDIS Strategic Plan (2005)	NOAA Mission Support	Provide timely and effective acquisition and delivery of satellite-derived information that supports requirements from the mission goals
			Provide applied research to ensure the quality, reliability, and accuracy of current and future satellite products and services to support the NOAA mission goals
		Geostationary Satellite Acquisition	By 2010, through its technology infusion planning activity, NESDIS will have determined the best methods for the following technologies: **… Microwave imaging and sounding systems from geostationary orbit**
	GOES-R (2004)	GPRD P3I requirements	(A large number of P3I products requires a microwave sounder)
	Hurricane Intensity WG (2006)	Science Advisory Board report	Reduce the error in 48-hour intensity forecasts for hurricane-strength storms by at least 10 kt within the next five years, with an emphasis on improved forecasting of rapid intensification and decay, and decay and reintensification cycles
			Improve hurricane observing systems
NRC	Decadal Survey (2007)	PATH mission	Needs: Early identification and reliable forecasting of the track and intensity of tropical cyclones Geographic distribution and magnitude of storm surge and rain accumulation totals during and after landfall Observations: 3D atmospheric temperature & water vapor; SST; precipitation; all-weather conditions (clear and cloudy); temporal refresh every 15-30 minutes
			Scientific objectives: Improve model representation of cloud formation, evolution and precipitation Use time-continuous all-weather observations to impose new constraints on models Mitigate requirements on models by enabling frequent re-initialization by observations Enable major scientific advances in understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S.
			Mission & payload: MEO or GEO; Recommend all-weather sensor suite on future GOES platforms; Require 50 or 118 GHz and 183 GHz; Microwave array spectrometer; Suitable for start in 2010 time frame

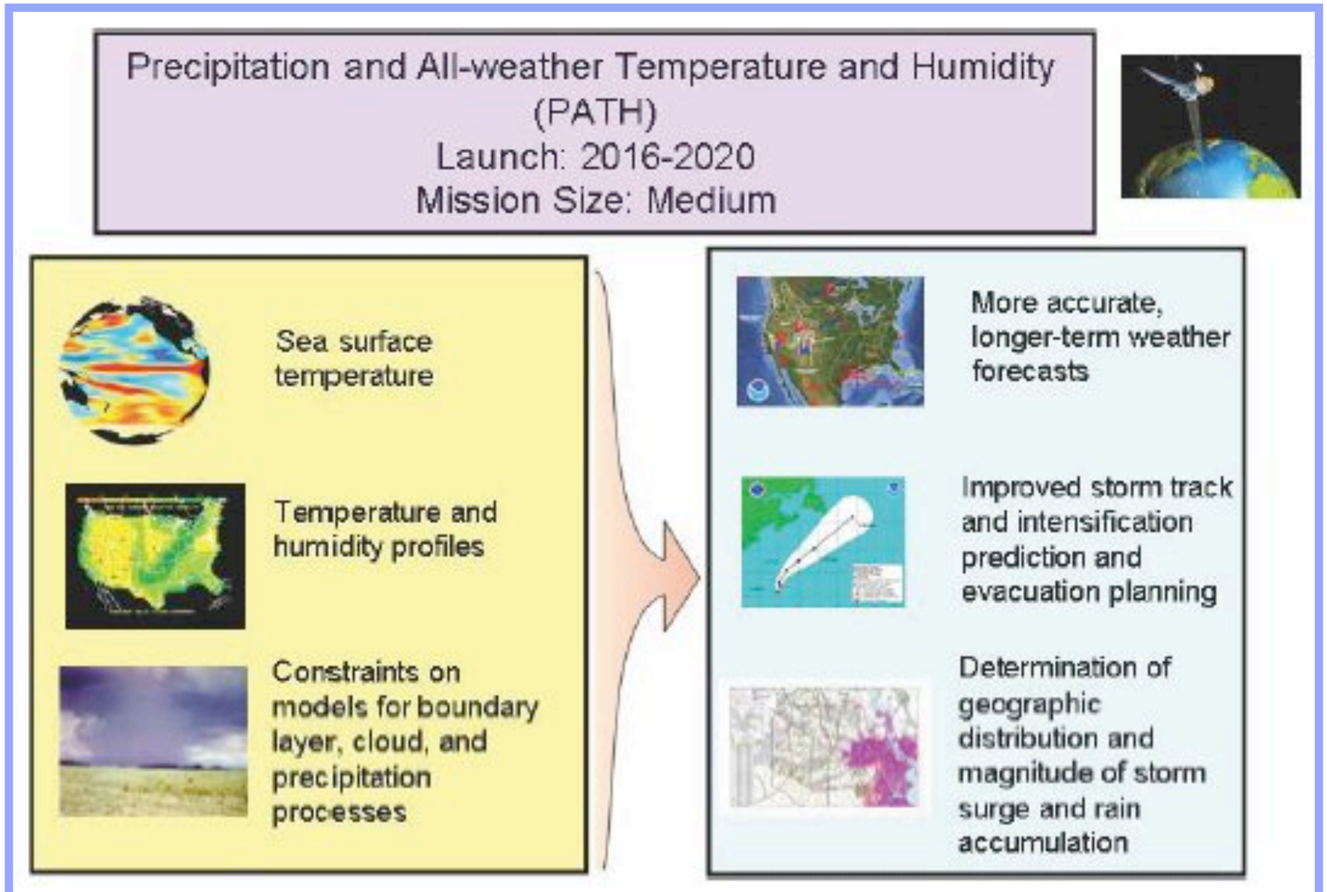
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

NRC Decadal Survey

NASA is committed to implementing the Decadal-Survey missions, but current funding of SMD/ESD dictates a stretched out schedule

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST*	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M



PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M

= GeoSTAR!

Note: The NRC panel put PATH in the 3rd tier, reflecting their perception of the maturity of the required technology
Recent developments indicate a higher level of readiness, and it may be feasible to implement PATH earlier than thought

Why GEO Microwave Sounders?

- **GEO sensors achieve high temporal resolution**
  - LEO: Global coverage, but poor temporal resolution; high spatial res. is easy
  - GEO: High temporal resolution and coverage, but only hemispheric non-polar coverage; high spatial res. is difficult
  - Requires equivalent measurement capabilities as now in LEO: IR & MW sounders
- **MW sounders measure quantities IR sounders can't**
  - Meteorologically "interesting" scenes
    - Full cloud cover; Severe storms & hurricanes
  - Cloud liquid water distribution
  - Precipitation & convection
- **MW sounders complement IR sounders**
  - Complement primary IR sounder (HES) with matching MW sounder
    - Until now not feasible due to very large aperture required (~ 4-6 m dia. in GEO)
  - Microwave provides cloud/"cloud-clearing" information
    - Requires T-sounding through clouds - to surface under all atmospheric conditions
  - *It may be possible to synergistically use ABI + MW in lieu of HES + MW*
- **A MW sounder is one of the most desired GEO payloads**
  - High on the list of unmet capabilities
  - Largest number of high-value applications

Why Not Just IR Sounders?

IR vs. MW: Pros & Cons

IR sounders vs. MW sounders

Spatial resolution

- --IR vs. MW: 10-15 km vs. 15-50 km hor.res.; 1-1.5 km vs. ~2 km vert.res.

Basic sounding accuracy

- --IR vs. MW: 1 K vs. 1.5 K for T(z); 15% vs. 20% for q(z); none vs. 40% for L(z)

Scene coverage

- --Cloud free: IR outperforms MW (but IR = MW in coverage)
- --Partly cloudy: IR < MW (IR depends on "cloud clearing", a noise-amplifying process)
- --Fully cloudy, storms: MW far outperforms IR ("cloud clearing" cannot be done)

Hurricanes & severe storms

- --IR can only see cloud tops, often obscured by cirrus shields
- --MW can see to surface (except in heavy precipitation: switch to convection observations)

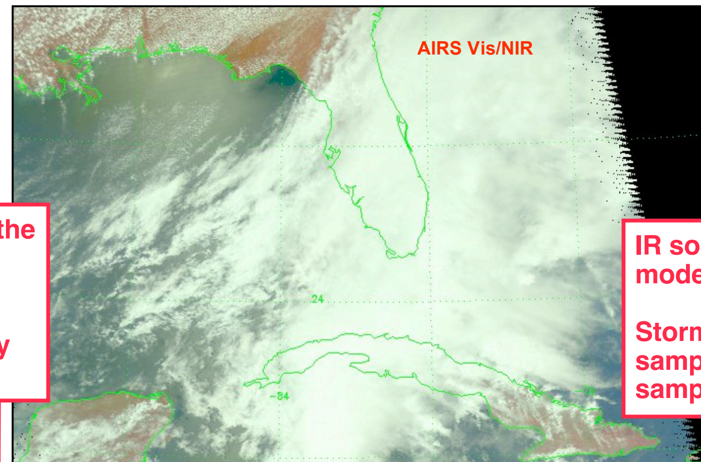
Summary

- --IR is best suited for global observations and storm precursor conditions in clear sky
- --MW is best suited for observing in/through storms and precursor conditions in clouds

Example

Tropical system near Florida observed with the Atmospheric Infrared Sounder (AIRS)

(May 16, 2006)

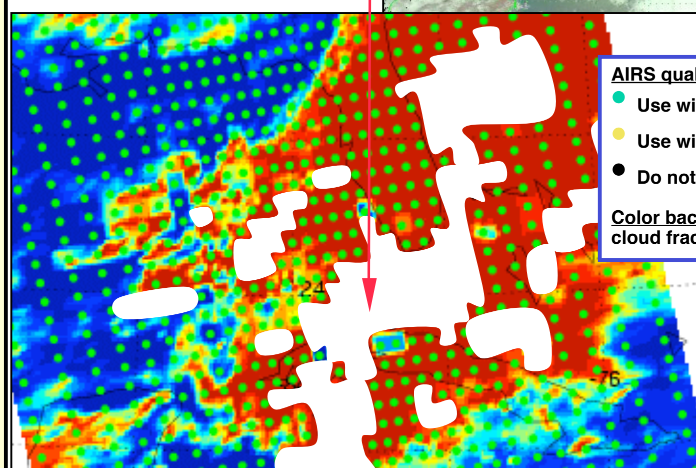


MW soundings fail only in the presence of precipitation with current algorithms

New algorithms will remedy that

IR soundings fail with even moderate cloud cover

Storm/cloud cases are not well sampled - i.e. there is significant sampling bias



AIRS MW-based retrievals

AIRS quality flags

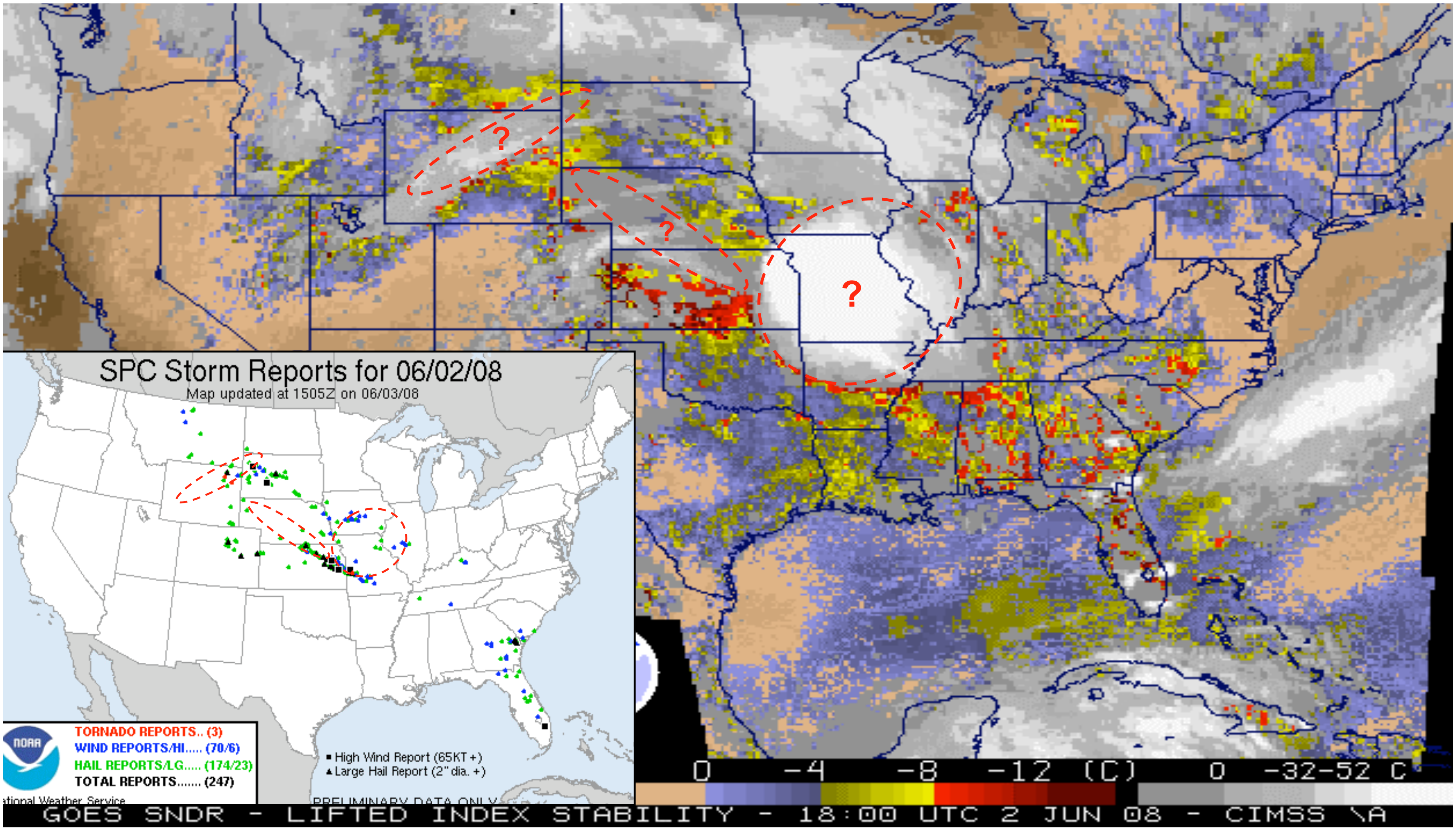
- Use with confidence
- Use with caution
- Do not use

Color background: cloud fraction

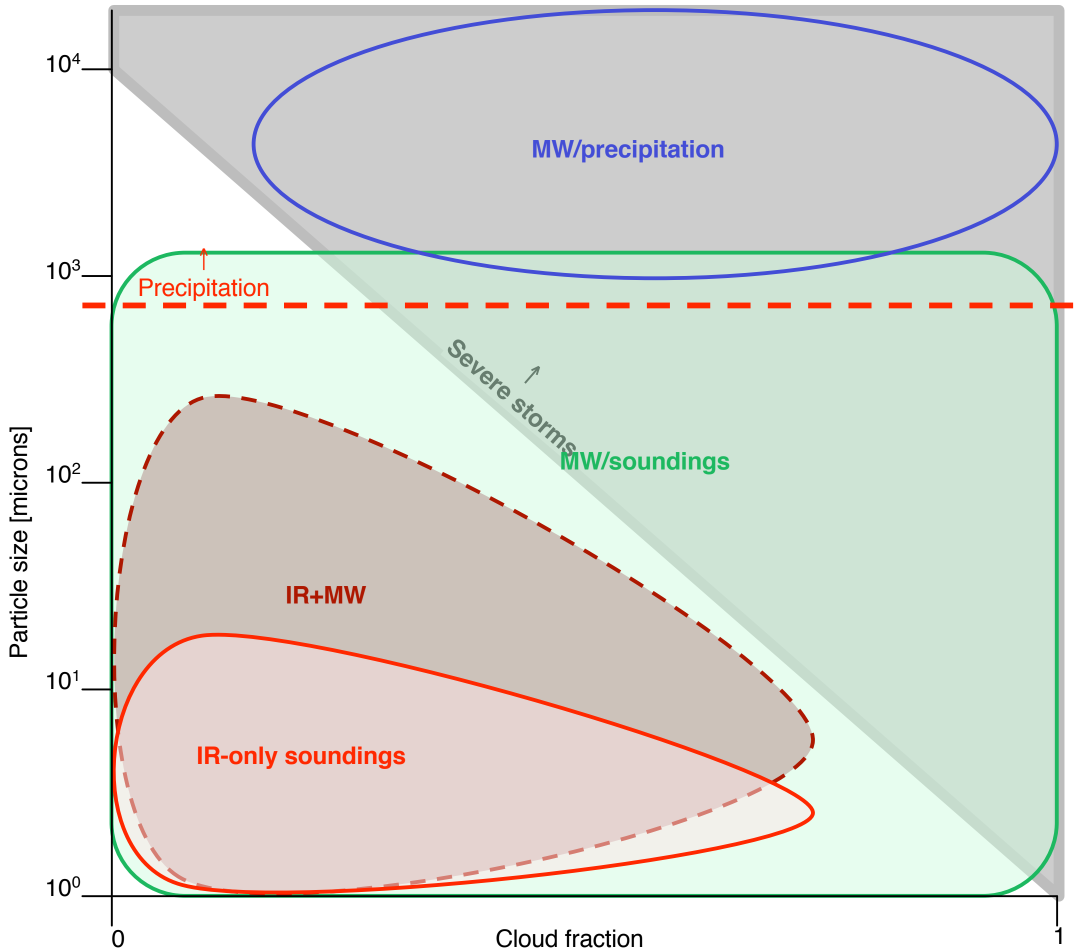
White: Poor retrievals

AIRS IR-based retrievals

What's Going On Below Those Clouds?



Weather Regimes vs. Obs. Domains

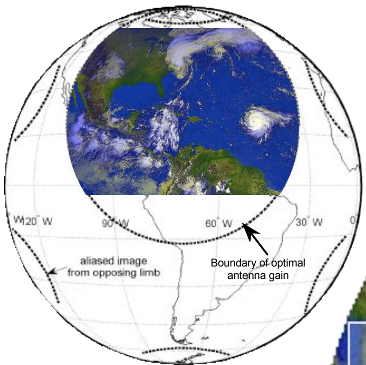


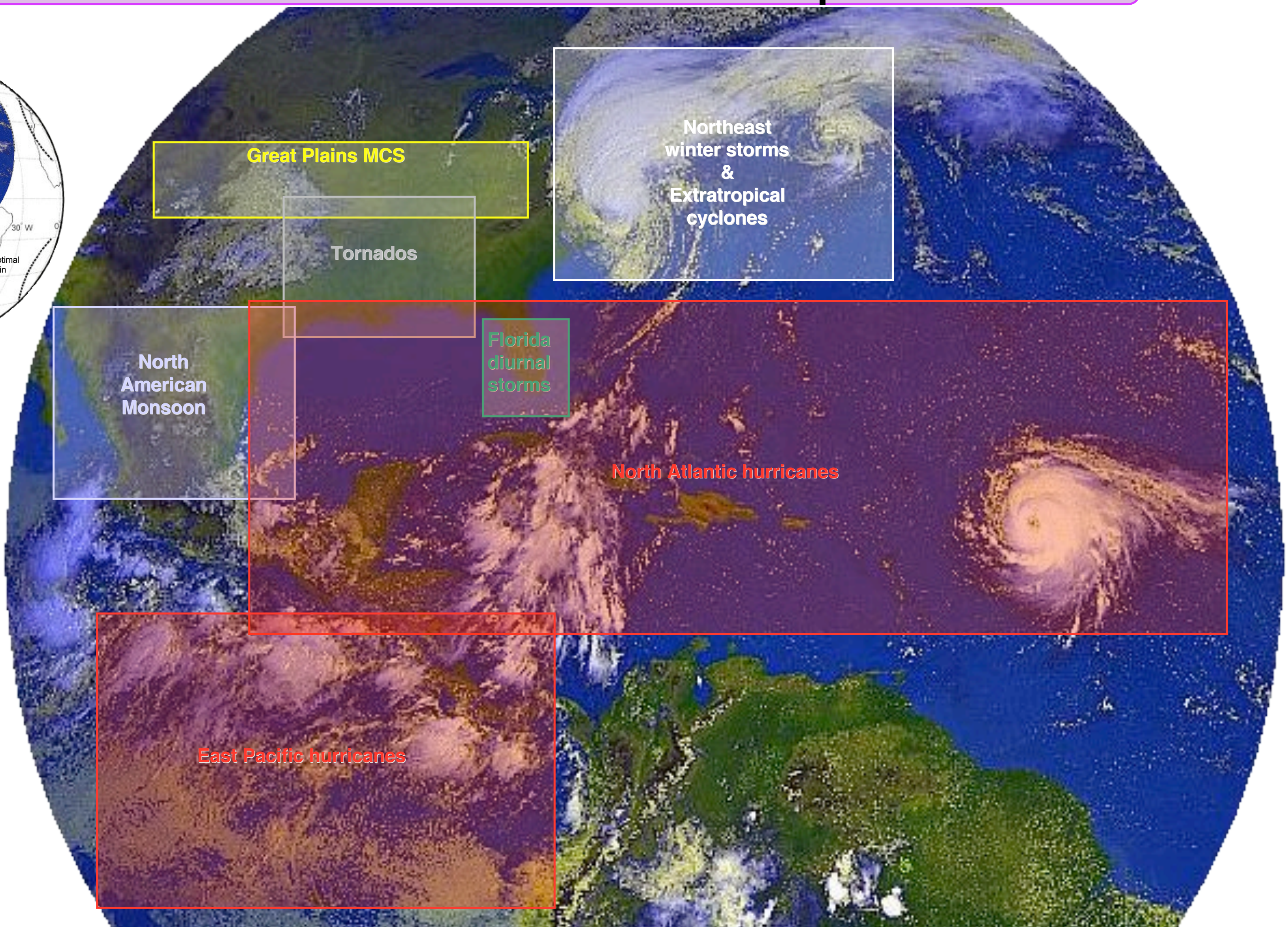
Note: This is a 2-D view of a multidimensional world
Additional dimensions include spatial and temporal scales

Observing Needs (simplified)

- **What do we need?**
  - Models: High resolution with correct/complete physics
    - Models must be **improved** with respect to **diurnal cycle**
    - Models must be **improved** with respect to **convective** microphysics
    - Model runs must be **initialized** with valid & complete **observations**
    - Initial conditions must be **validated** with **current observations**
  - Observations: "Storm sensors" with frequent observations
    - Observations **inside & below storm**
    - Capture **microphysics** and mesoscale **dynamics**
    - Accurate real-time observations for **diagnostics, assessment & analysis**
    - Frequent/continuous observations $\Rightarrow$ **GEO satellites**, "dwelling" UAS
      - Full resolution of diurnal cycle
      - Complete storm life-cycle
- **This requires…**
  - **Better fidelity, higher resolution, deeper penetration, vertical structure, time-continuous & complete life-cycle observations**

U.S. Science Focus Topics





Science Topic: Tropical Cyclones

Science question: How can we improve hurricane intensity observations?

- Current capabilities and their limitations
  - Aircraft flights: Sparsely sampled
  - QuickScat: Sampled 1–2x per day, obscured by rain
  - TRMM: Sampled 1–2x per day
  - GOES/IR (Dvorak): Cloud tops only, indirect empirical
  - AMSU & SSM/I: Each storm sampled 1–3x per day (varies)

- GeoSTAR capabilities
  - Continuous monitoring
  - Measure warm core anomaly
  - Measure rain rate, convective intensity
  - Infer all-weather wind vector profiles

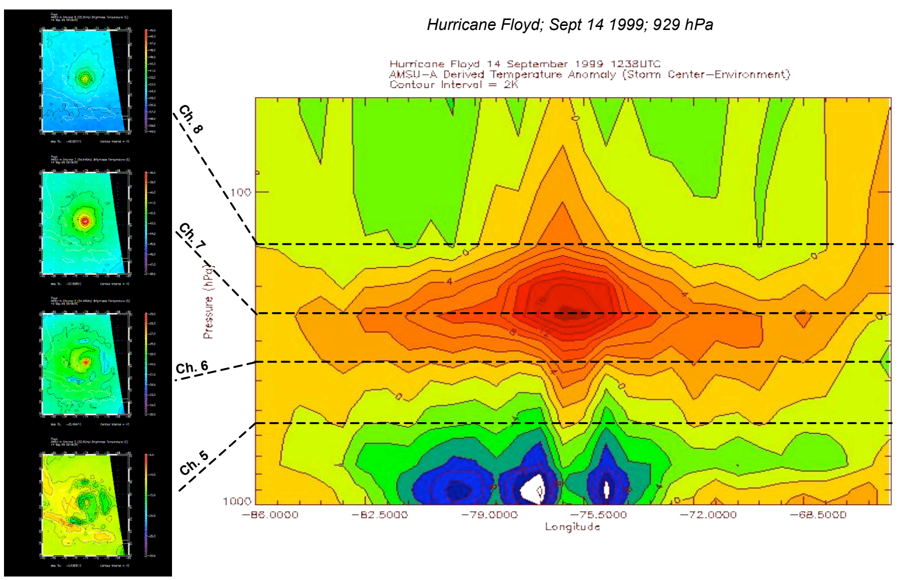
Example: Inferring hurricane intensity from warm core anomaly

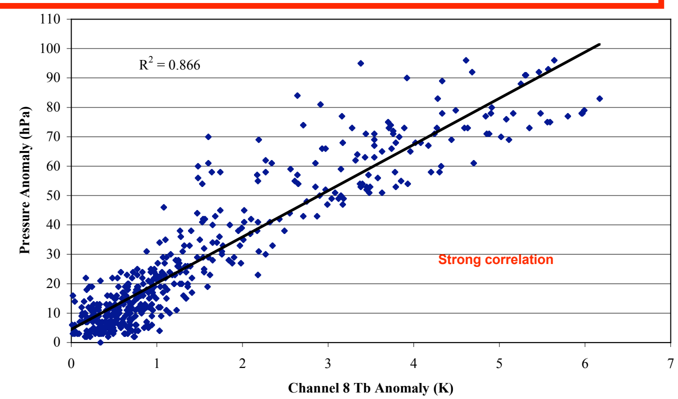
Strong correlation between microwave brightness temperature anomaly and pressure anomaly in hurricane core

Method using AMSU-A microwave sounder data developed by U. Wisconsin and NRL

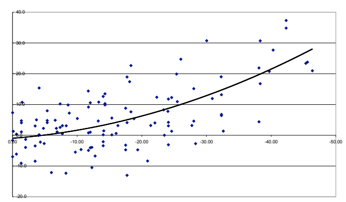
AMSU-A

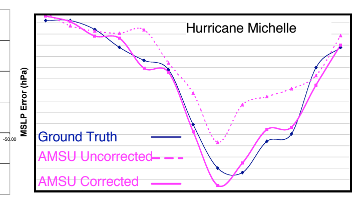
Hurricane Floyd; Sept 14 1999; 929 hPa





Can correct for near-miss and FOV-eye mismatch





C. Velden/UW
J. Hawkins/NRL

Science Topic: Convective Systems

Science question: How can we improve understanding of storm dynamics?

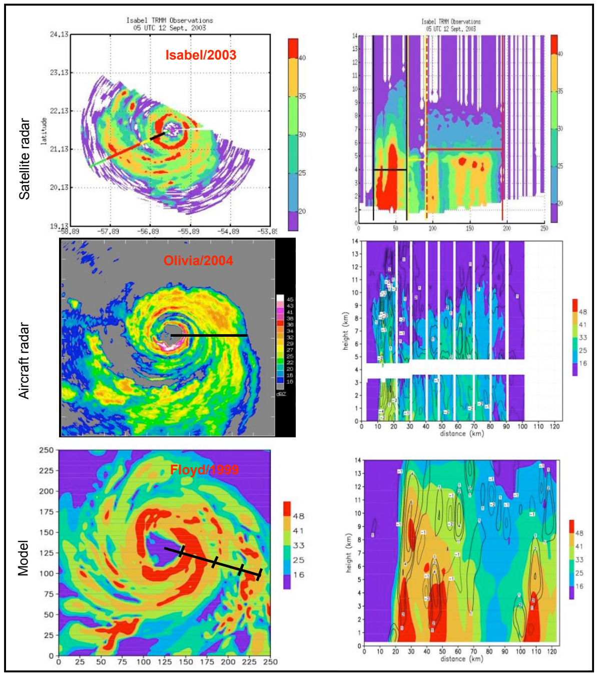
- Issues and problems
  - Deficient models
  - Deficient forecast initialization
  - Incomplete observations: sparse/incomplete storm obs.
  - Sparse observations of microphysics

- GeoSTAR solutions
  - GeoSTAR will mimic precipitation/cloud radar
  - Use to diagnose/fix model deficiencies
  - Initialize with current, complete state variables
  - Re-initialize with current observations

Example: Radar reflectivity is a measure of internal storm processes

Models get the equivalent radar reflectivity wrong due to faulty microphysics

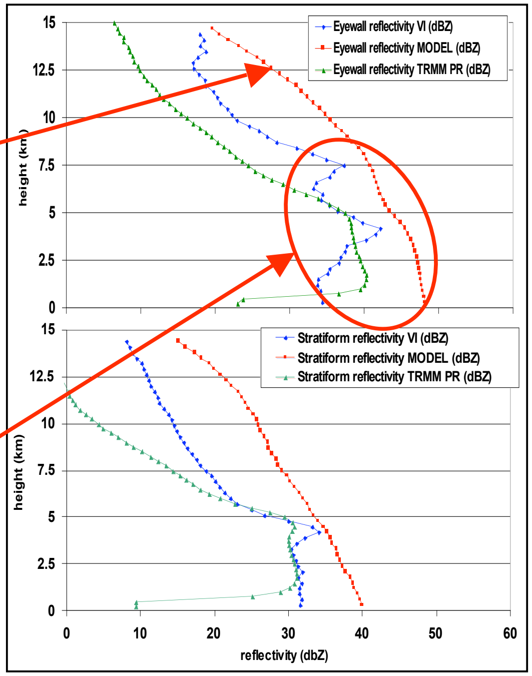
Significant intensity forecast improvement requires model improvements



The model (MM5) consistently overestimates radar reflectivity at all altitudes

The model does not capture the vertical structure well

R. Rogers/NOAA-HRD
R. Atlas/NOAA-AOML



Science Topic: Great Plains MCS storms

Science question: How can we improve understanding of continental storms?

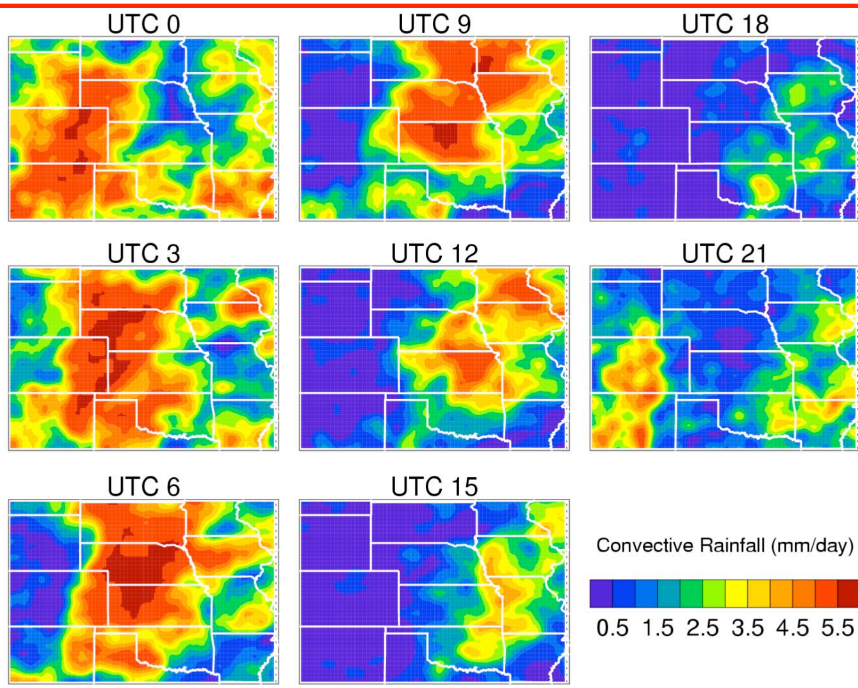
- Issues and problems
  - Convection shows very strong diurnal cycle
  - Poorly sampled by satellites
  - Models show significant amplitude and phase errors

- GeoSTAR solutions
  - Diurnal cycle fully resolved
  - Convection/rain measured in RT
  - Atmospheric stability measured concurrently

Example: MCS-storms originating in Eastern Rockies and propagating east

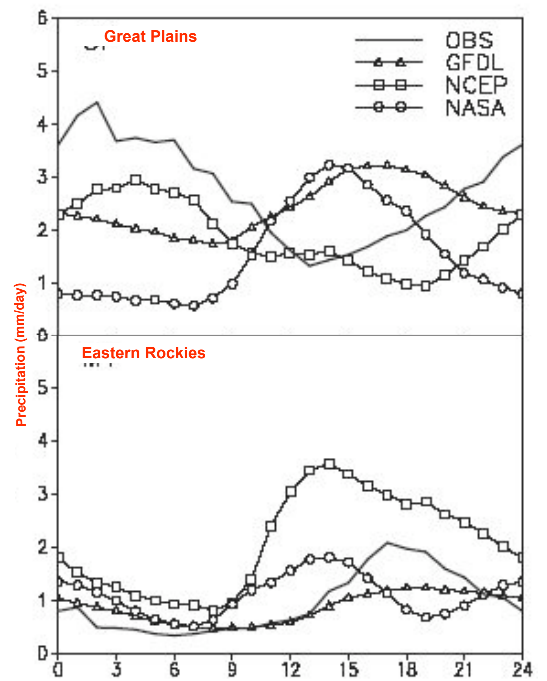
Potential for destructive weather events is very great

Models, forecasts & warnings must be improved



B. Tian/JPL

Strong diurnal cycle & rapid propagation from Rockies across Great Plains



Many models have diurnal cycle wrong

Science Topic: North American Monsoon

Science question: How can we improve understanding of hydrology cycle?

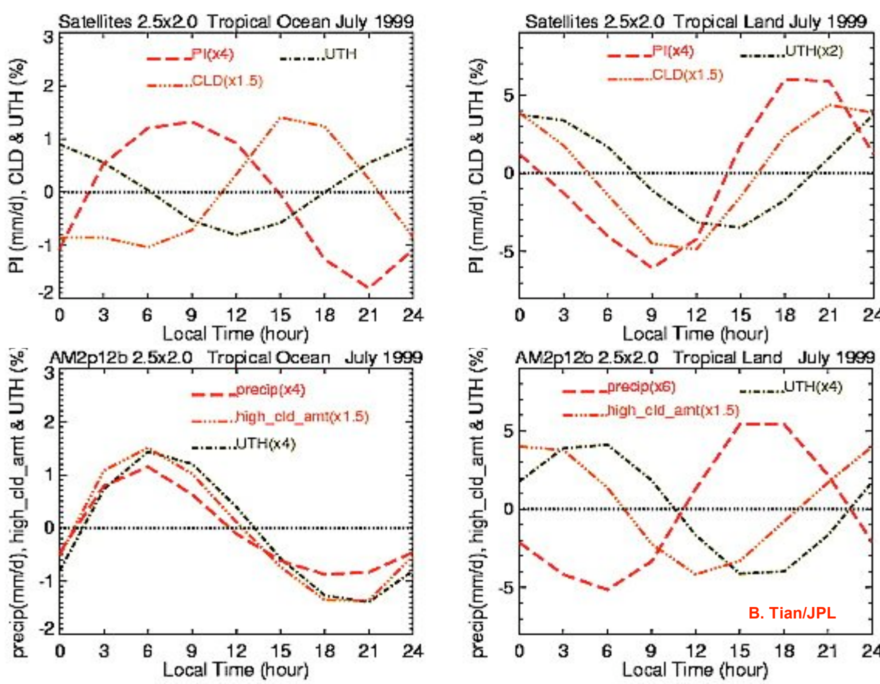
- Issues and problems
  - Convection shows very strong diurnal cycle
  - Poorly sampled by satellites
  - Models show significant amplitude and phase errors

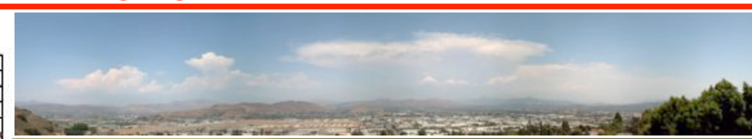
- GeoSTAR solutions
  - Diurnal cycle fully resolved
  - Convection/rain measured in RT
  - Moisture and clouds measured concurrently

Example: Tropical moisture flow into US through N.A. Monsoon

Causes severe thunder storms, even tornadoes; potential for flash floods

Models need improvement; now-casting of great value





Models OK re: precipitation but not re: UTH and clouds

Monsoon thunder storms can spawn tornadoes (Salt Lake City)

Science Topic: Florida Sea Breeze Storms

Science question: How can we improve modeling of tropical thunder storms?

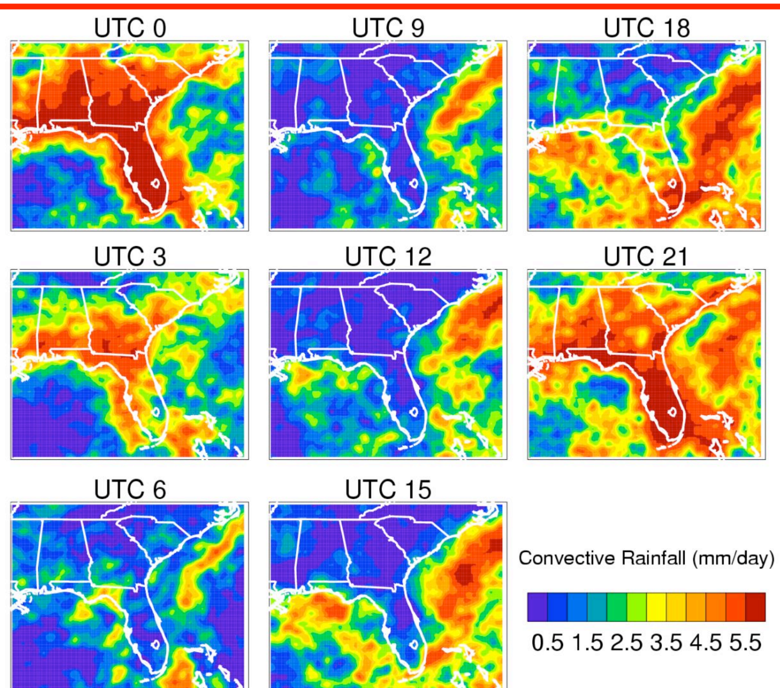
- Issues and problems
  - Convection shows very strong diurnal cycle
  - Poorly sampled by satellites
  - Models show significant amplitude and phase errors

- GeoSTAR solutions
  - Diurnal cycle fully resolved
  - Convection/rain measured in RT
  - Atmospheric stability measured concurrently

Example: Severe thunder storms in Florida

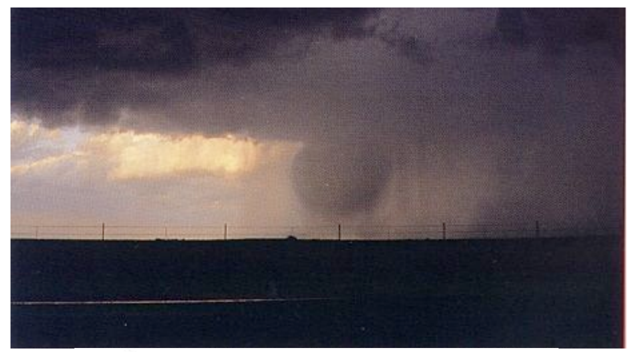
Potential for destructive weather; fire danger from lightning strikes; flooding; hail damage

Forecast models must be improved

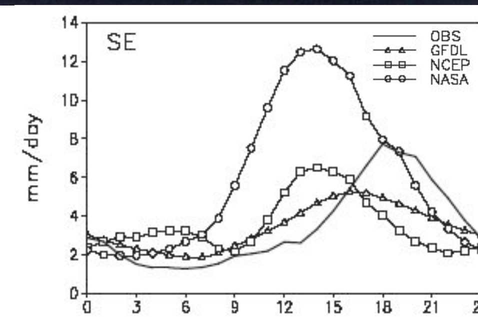


B. Tian/JPL

Strong diurnal cycle peaks in late afternoon local time



NOAA



M. Lee/UMBC

Models disagree on phase and amplitude

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Numerical Weather Prediction

Science question: How can weather forecast duration and reliability be improved?

- Issues and problems
  - Models deficient re: clouds and convection
  - Initialization data deficient, incomplete, obsolete
  - Cause: sparse and incomplete observations in storms
  - Result: poor storm forecasts

- GeoSTAR solutions
  - Use obs. to diagnose and fix model problems
  - Initialize with current, complete state variables
  - Re-initialize with current observations
  - Nudging and phase-correction/4DVAR

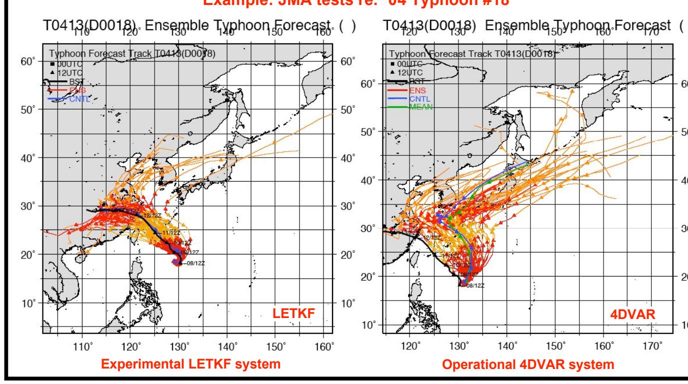
Example: New Assimilation Methods Under Development

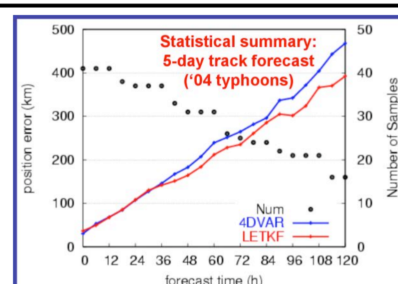
Can use *continuous* obs. of "process measures" in stormy areas: rain, clouds, stability

These observations will be provided by GeoSTAR

- Two methods that potentially can assimilate continuous information from PATH:
  - 4D-Var
  - 4D-Ensemble Kalman Filter: Local Ensemble Transform Kalman Filter (LETKF)
- 4D-LETKF works well and is simple. It is being tested at JMA, NCEP, Brazil and being considered for testing at ECMWF (see figures).
- The analysis in 4D-LETKF is a linear combination of the ensemble forecast members. When assimilating CAPE, for example, the member with CAPE closest to observations will simply be given more weight.
- In the next few years we will develop considerable experience with the assimilation of these "unconventional" but important observations.
- GeoSTAR will provide estimates of cloud, precipitation, CAPE (stability), as well as moisture-tracked winds, in and near storm areas, where they are most needed.
- The new 4D data assimilation methods can for the first time assimilate this important source of observations (GeoSTAR) that should result in major improvements in the prediction of storms and hurricanes.

Example: JMA tests re. '04 Typhoon #18



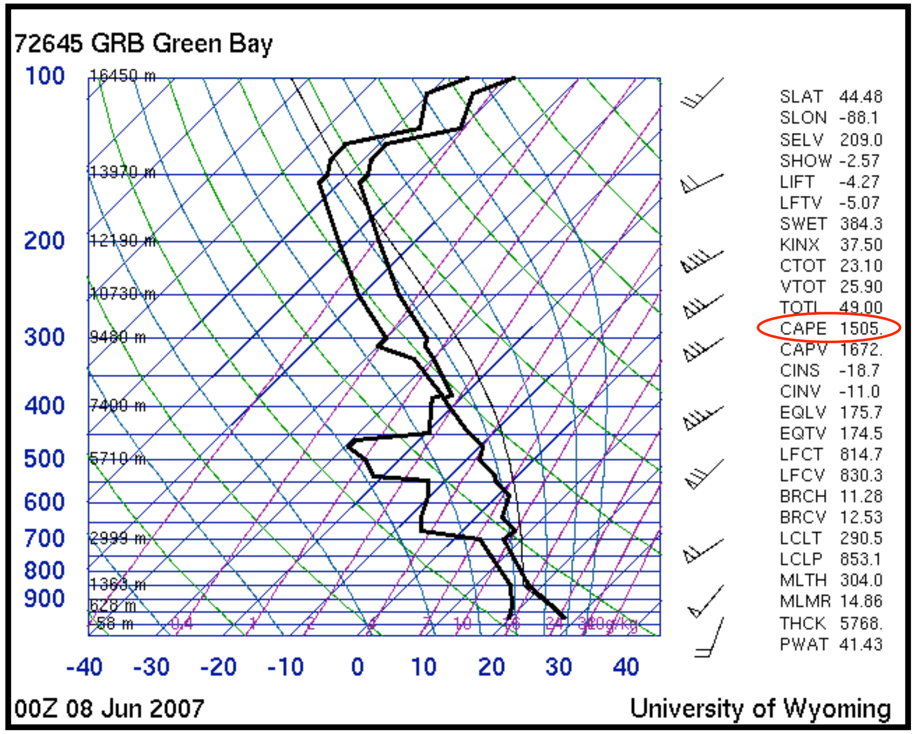


E. Kalnay/UMD

Key Data Products: Atmospheric Stability

Atmospheric stability indices
- LI, CAPE, etc.
- Derived from sounding profiles
- Crucial in detection of severe-storm precursor conditions

- Current capabilities
  - Poorly observed
    - In-situ: Few, fixed locations (raobs)
    - LEO satellites: Sampled 1–2x/day
    - GEO satellites: IR only ⇒ clear only
  - Poorly predicted
    - Models deficient in severe conditions
- GeoSTAR capabilities
  - Clear *and* cloudy conditions
    - Observe IN storms (except heavy precipitation)
  - Every 15–30 minutes everywhere
    - Observe storms develop



Example Skew-T diagram during tornado outbreak in Wisconsin

http://weather.uwyo.edu

Key Data Products: Precipitation

Current capabilities

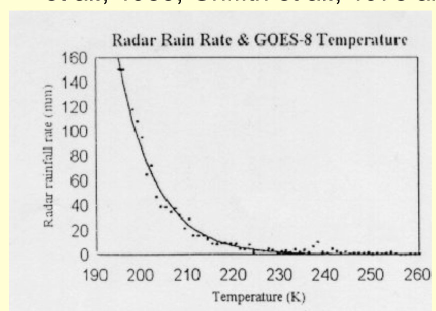
- Poorly sampled
  - In-situ: Few, fixed locations
  - Radar: Regional coverage only
  - LEO satellites: Sampled 1–2x/day
  - GEO satellites: IR only Û indirect
- Poorly predicted
  - Models deficient re: convective processes

GeoSTAR capabilities

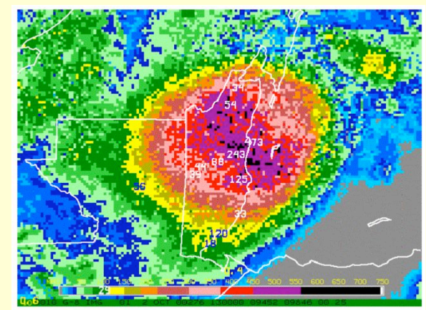
- Derived from scattering signature
  - All conditions and locations, every 15 min
  - Observe storms develop
- Continuously calibrated to GPM
- Applicable algorithms available
  - NOAA (Weng et al.)
  - UW (Bennartz et al.)
  - MIT (Staelin et al.)
  - Others under development

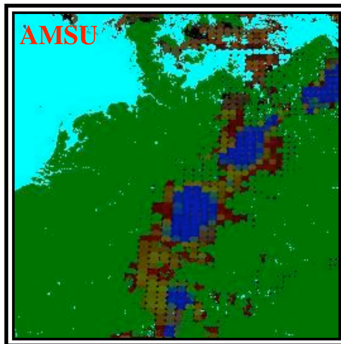
NOAA's Rainfall Auto-Estimator falls short

1. **Rain relationship**—computed from pairs of GOES-8 10.7-μm IR images and collocated instantaneous radar rainfall estimates from the U.S. operational network (U.S. central plains and the Gulf of Mexico)
2. **Moisture correction factor**—based on the product of PW and RH (sfc-500 mb) from the ETA model forecast for the nearest synoptic time—used to decrease surface rainfall in dry environments while increasing surface rain in moist environments
3. **Cloud growth rate correction factor and the cloud top temperature gradient**. The correction for rate of cloud top growth or decay uses collocated pixels in two consecutive half hour images. A convective system is more active and produces the greatest rainfall rates when the tops are becoming colder and expanding (Woodley et al., 1985, Griffith et al., 1978 and Scofield, 1977).



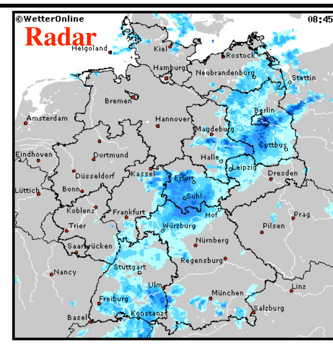
C. Kummerow





Example precipitation product derived from LEO/MW sounder (AMSU)

Red: light rain
Green: moderate
Blue: heavy



R. Bennartz

Advantages of GeoSTAR

- Strong physical correlation with precipitation process
- Observe associated H_2O profiles directly
- Geostationary: growth/decay and life cycle analysis

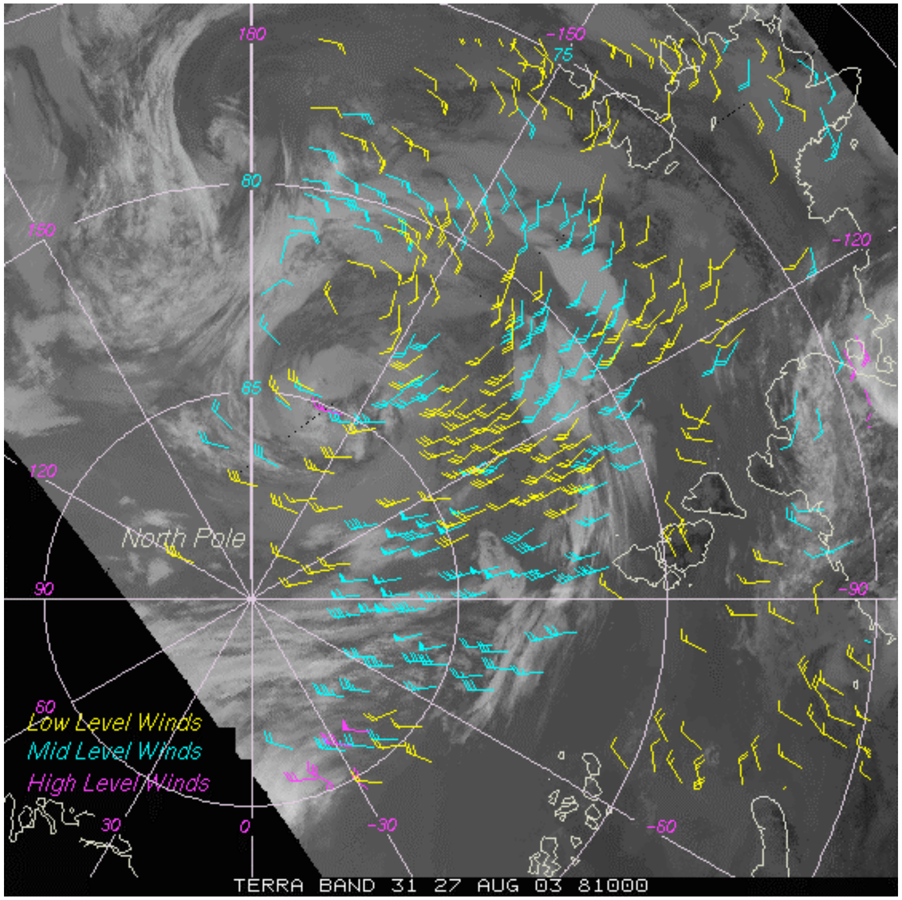
Element in GPM constellation!

Key Data Products: Tropospheric Wind

Tropospheric wind vector profiles

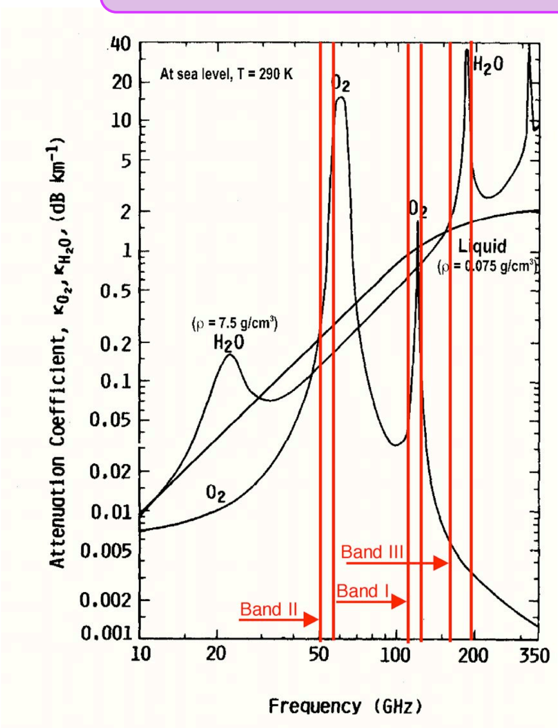
- Derived from moisture feature tracking
- Key parameter for improved numerical weather prediction
- *Tropospheric* wind (esp. at 500 mb) will have more impact on forecast accuracy than *surface* wind

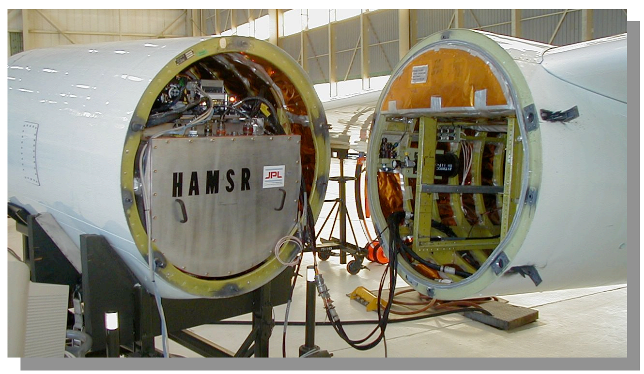
- Current capabilities
  - LEO satellites: MODIS
    - Polar regions only
    - Limited-accuracy water vapor profiles
  - GEO satellites: IR sounder
    - Poor sampling: clear only
    - Uncertain height assignment
  - GEO satellites: IR/Vis imager
    - Cloud tracking: cloud tops only
- GeoSTAR capabilities
  - Clear *and* cloudy
    - Including below clouds
  - Continuous: no time gaps
  - Applicable algorithms available
    - UW (Velden et al.)



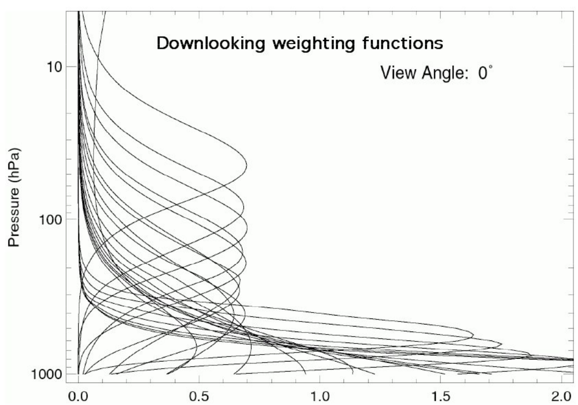
Example wind vectors from MODIS

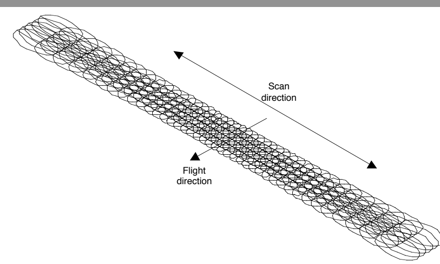
Aircraft Observations → New Algorithms

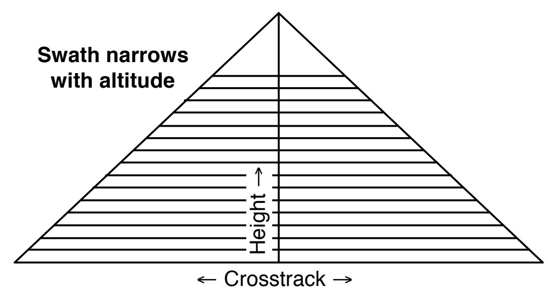




Chan #	Center freq. [GHz]	Offset [GHz]	Bandwidth [MHz]	Wt-func. Peak [mb or mm]
I-1	118.75	-5.500	1500	Sfc/[30 mm]
I-2	"	-3.500	1000	Surface
I-3	"	-2.550	500	Surface
I-4	"	-2.050	500	1000 mb
I-5	"	-1.600	400	750 mb
I-6	"	-1.200	400	400 mb
I-7	"	±0.800	2x400	250 mb
I-8	"	±0.450	2x300	150 mb
I-9	"	±0.235	2x130	80 mb
I-10	"	±0.120	2x100	40 mb
II-1	50.30	0	180	Sfc/[100 mm]
II-2	51.76	0	400	Surface
II-3	52.80	0	400	1000 mb
II-4	53.596	±0.115	2x170	750 mb
II-5	54.40	0	400	400 mb
II-6	54.94	0	400	250 mb
II-7	55.50	0	330	150 mb
II-8	56.02 56.67	0	270 330	90 mb
III-1	183.31	-17.0	4000	[11 mm]
III-2	"	±10.0	2x3000	[6.8 mm]
III-3	"	±7.0	2x2000	[4.2 mm]
III-4	"	±4.5	2x2000	[2.4 mm]
III-5	"	±3.0	2x1000	[1.2 mm]
III-6	"	±1.8	2x1000	[0.6 mm]
III-7	"	±1.0	2x500	[0.3 mm]



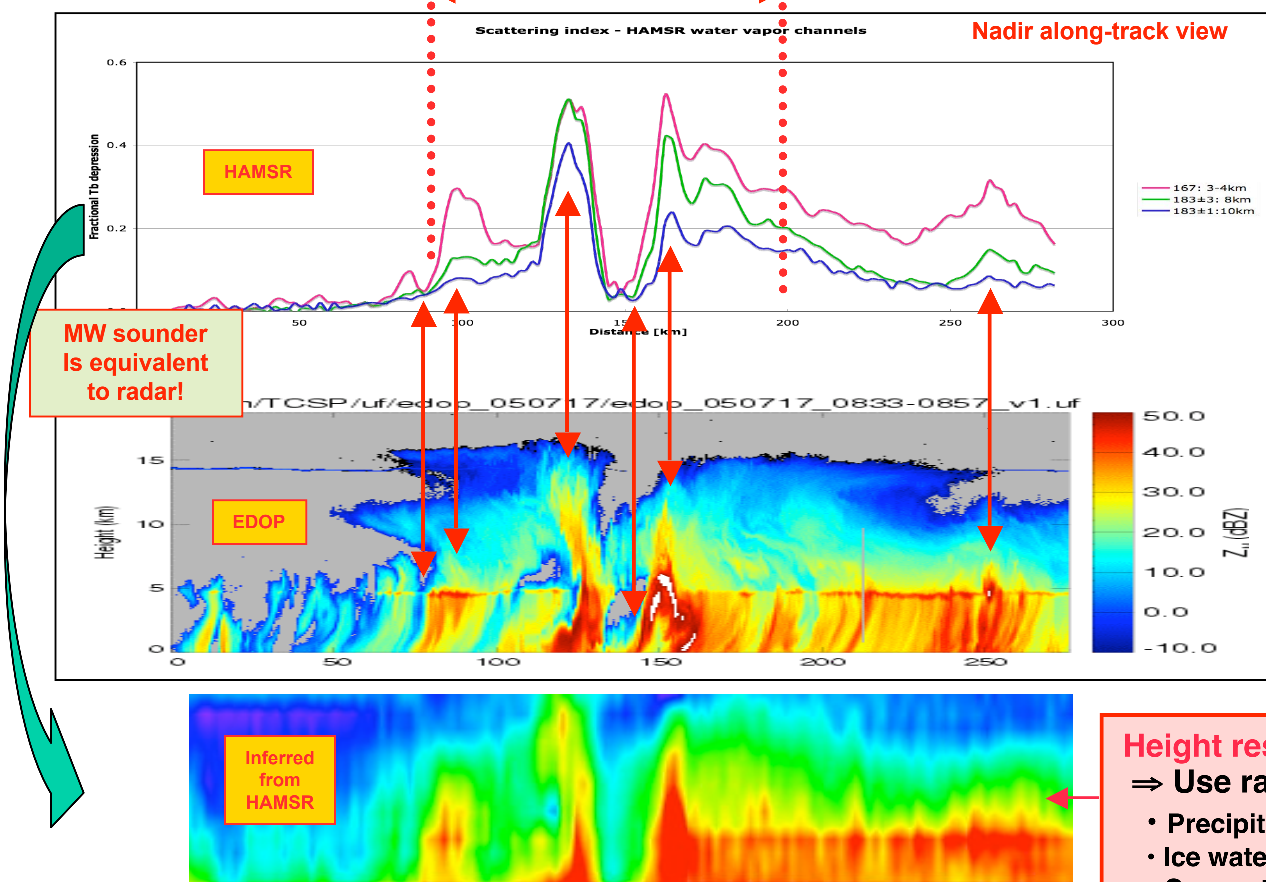


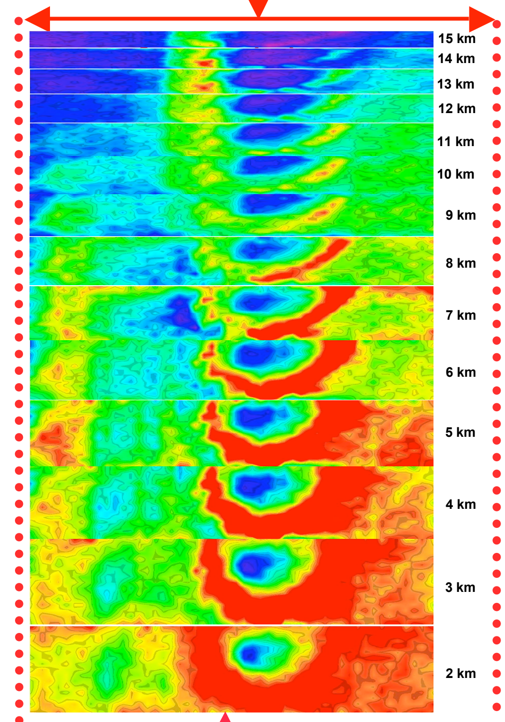


New Data Product: "Radar Reflectivity"

Hurricane observations with MW sounder (HAMSR) compared with doppler radar (EDOP)
Observations from NASA TCSP campaign, Costa Rica, 2005

Vertical slicing through hurricane Emily - July 17, 2005





Correlation between MW-sounder ΔTb and radar reflectivity exceeds 90% at all levels except near surface

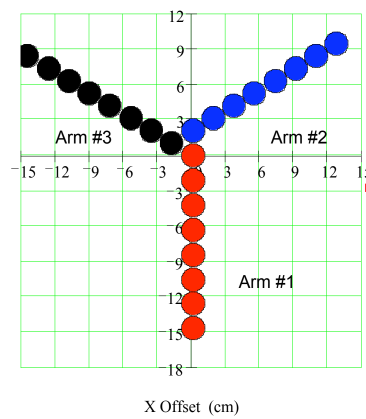
Height resolved "Radar reflectivity"
⇒ Use radar algorithms to derive
- Precipitation rate
- Ice water path
- Convective intensity
- Vertical structure

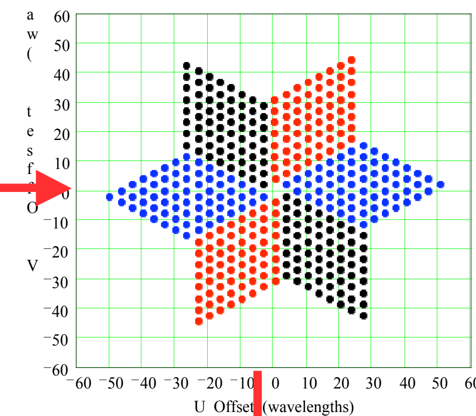
GeoSTAR System Concept

- **Aperture-synthesis concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One "Y" per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth

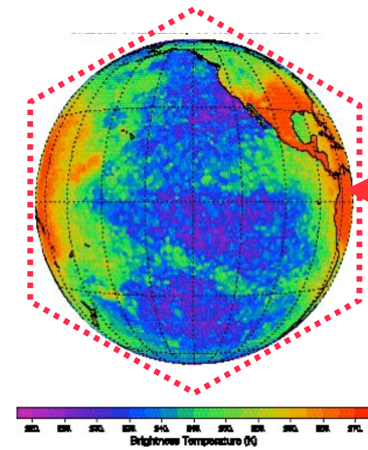
No moving parts!

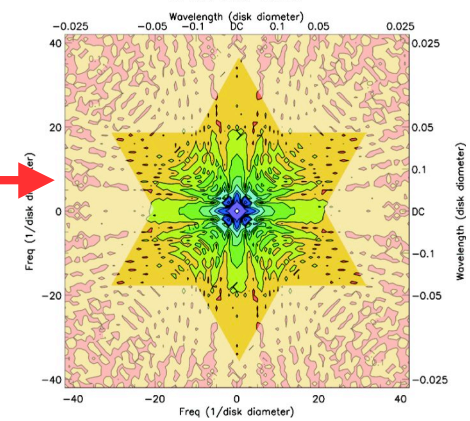
Receiver array & resulting uv samples





Example: AMSU-A ch. 1





National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

GeoSTAR Prototype Development

Objectives

- –Technology risk reduction
- –Develop system to maturity and test performance
- –Evaluate calibration approach
- –Assess measurement accuracy

Small, ground-based

- –24 receiving elements - 8 (9) per Y-arm
- –Operating at 50-55 GHz
- –4 tropospheric AMSU-A channels: 50.3 - 52.8 - 53.71/53.84 - 54.4 GHz
- –Implemented with miniature MMIC receivers
- –Element spacing as for GEO application (3.5 λ)
- –FPGA-based correlator
- –All calibration subsystems implemented

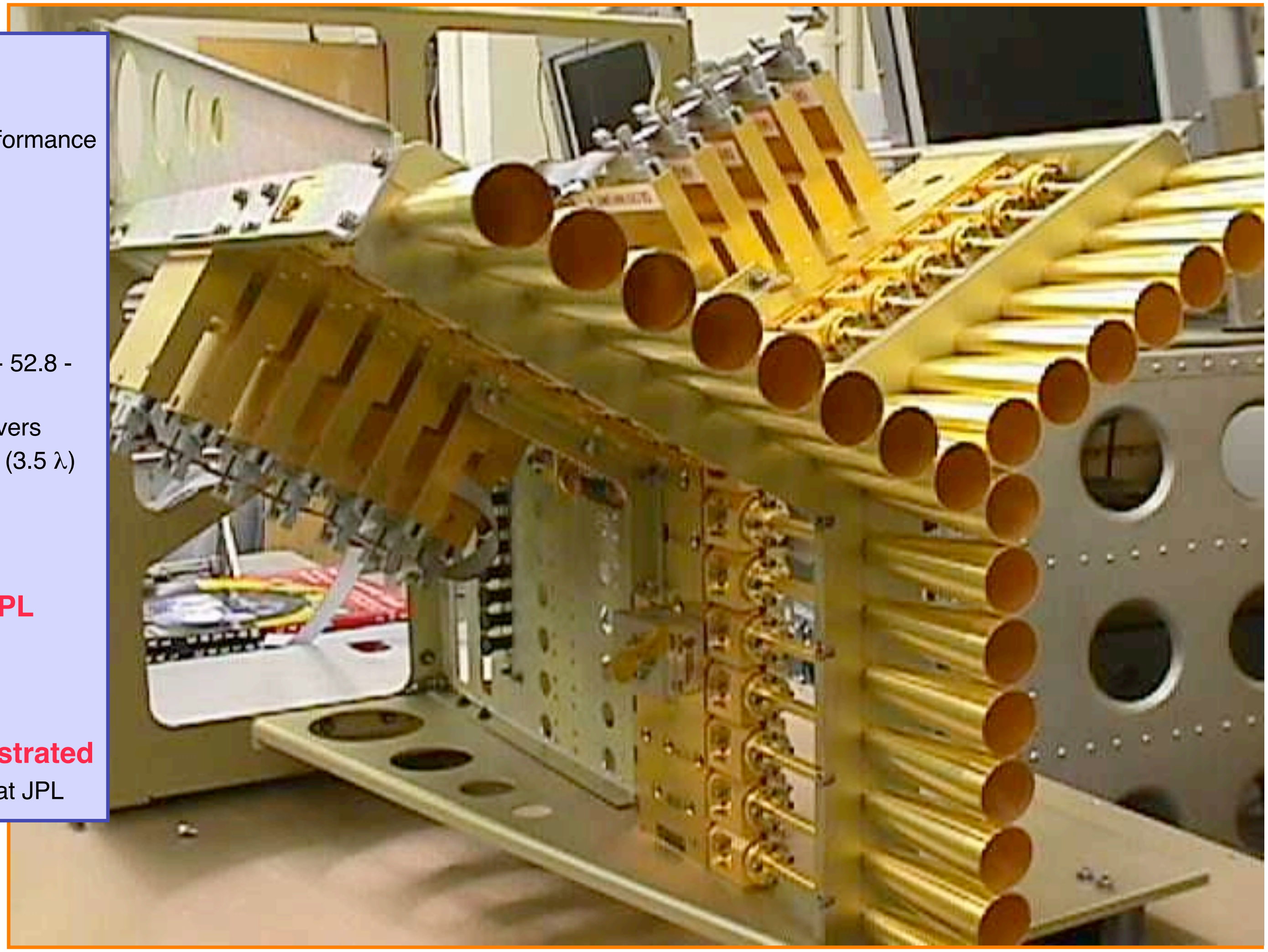
Has been thoroughly tested at JPL

Performance is excellent

Breakthrough development!

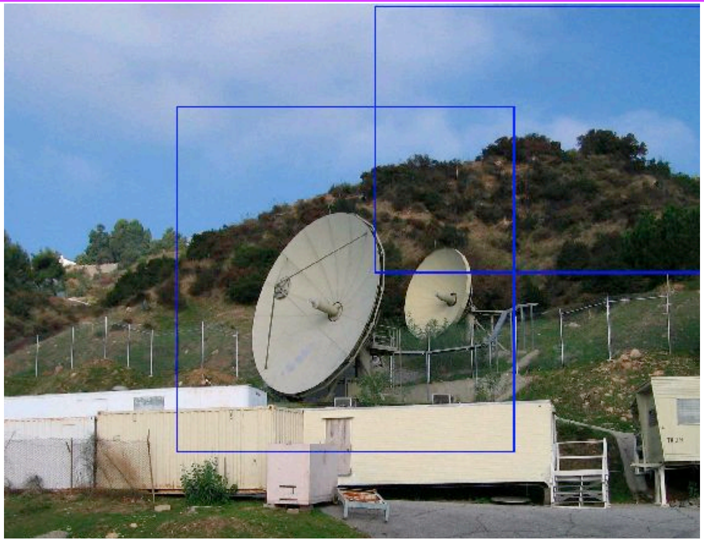
Ground-based sounding demonstrated

Observed diurnal cycle of T-inversion at JPL



First Images of Real Scenes

November 2005



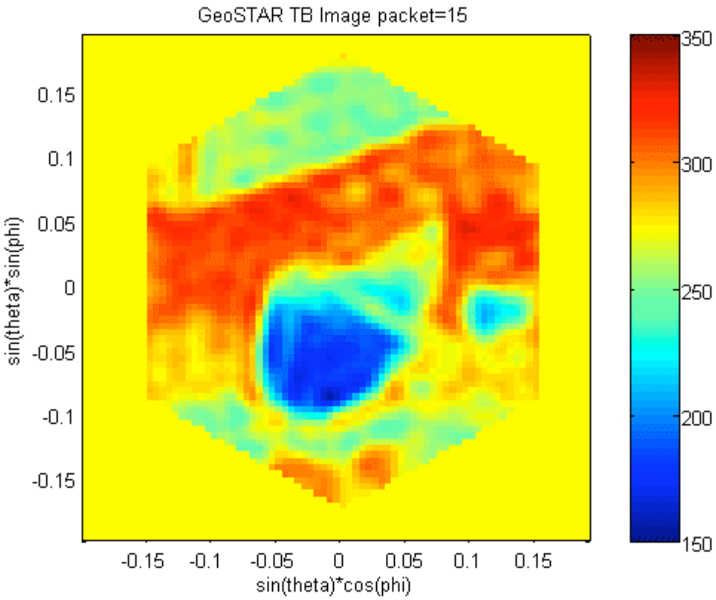
-Images reconstructed from 5-minute interferometric measurement sequences

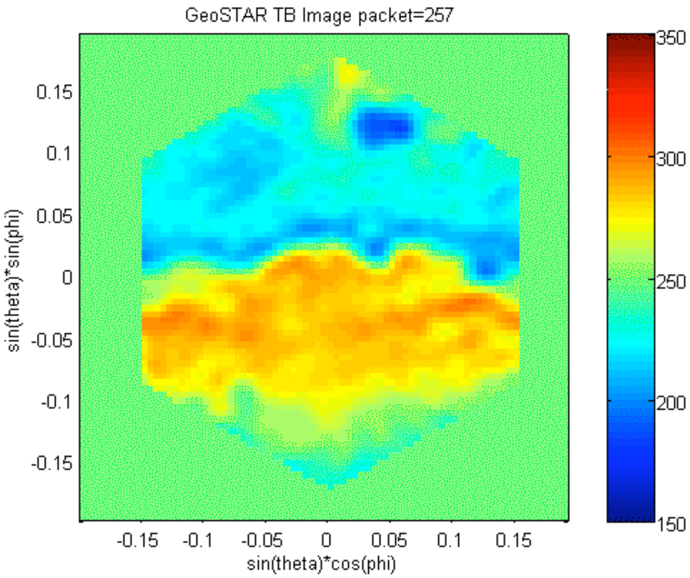
-Hexagonal central imaging area shown

-Aliasing from outside central imaging area can be seen

> **These effects are well understood and can be compensated for, but they will not appear in GEO (background Is 2.7 K)**

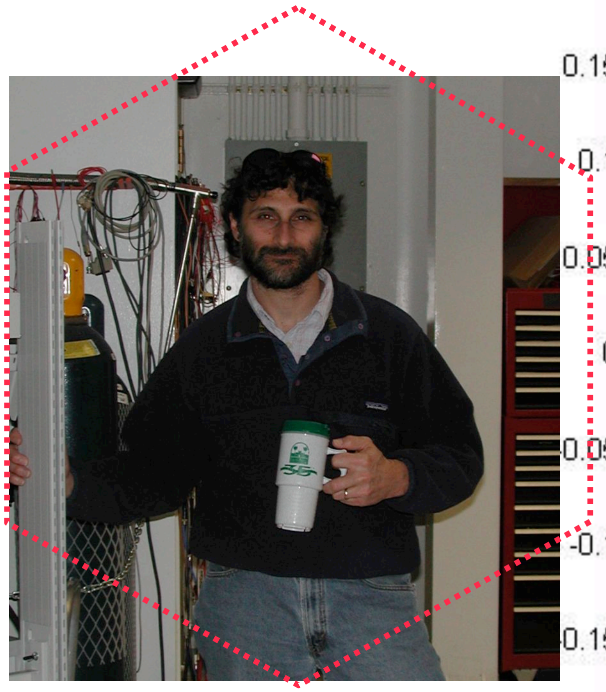
This was a first - a major achievement!

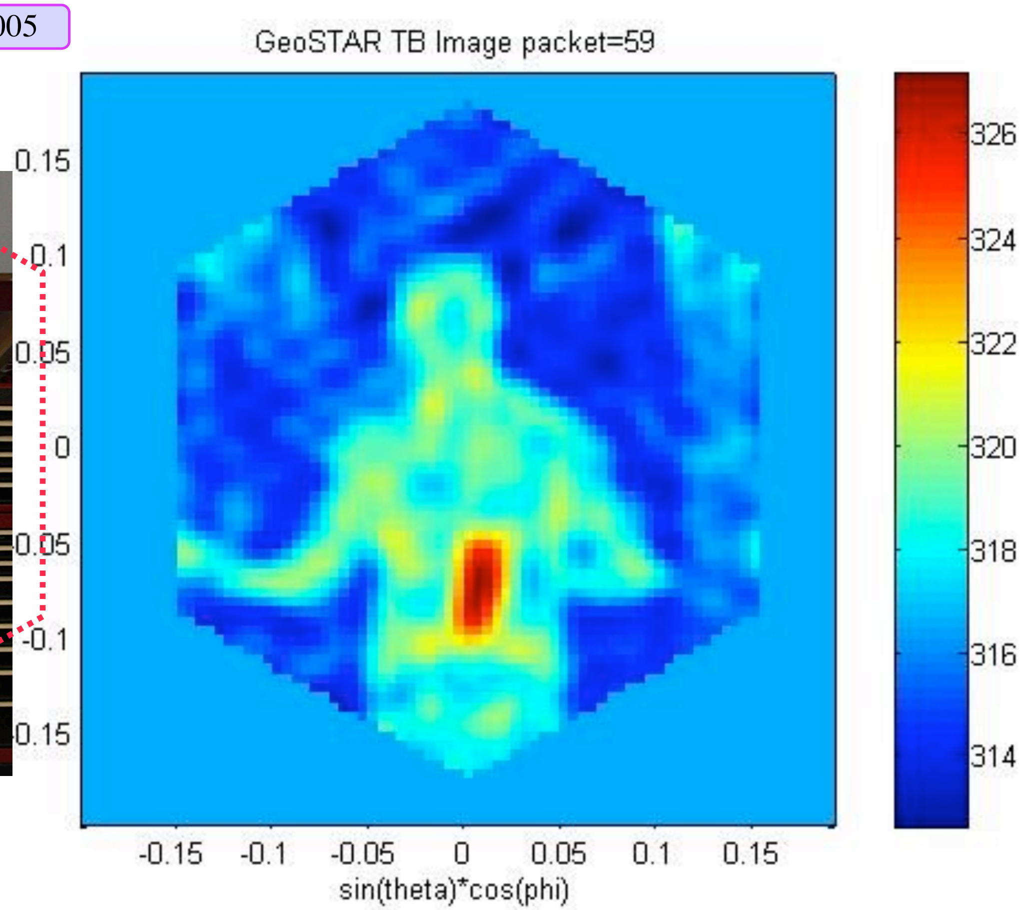




Indoor Target!

November 2005





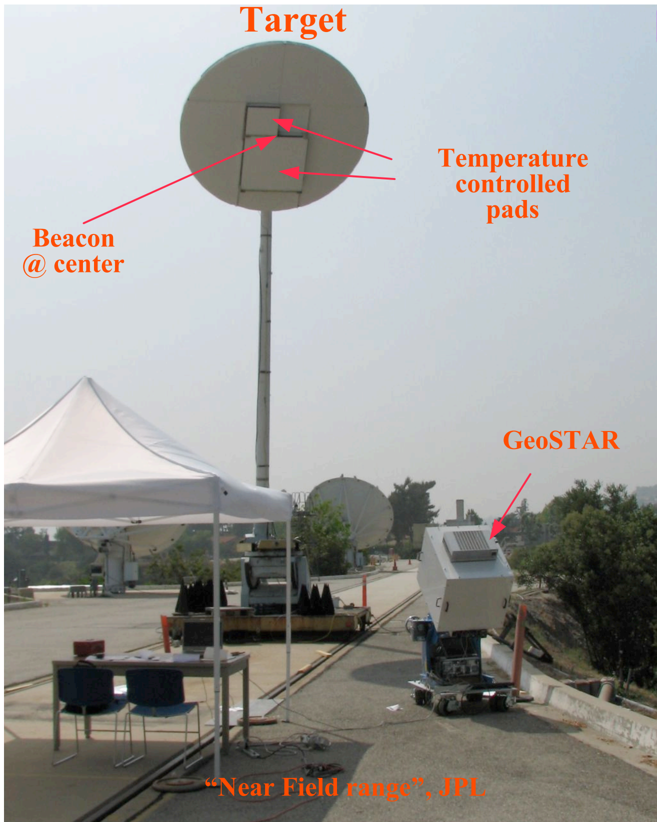
-Developed a method to compensate for distortions when target is in near field

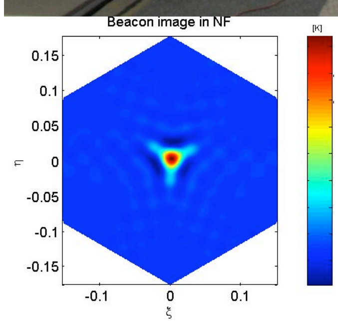
-Enables using near-field targets to measure the performance of the system

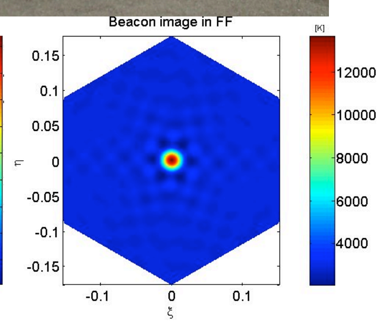
-Developed a mocked-up "Earth from GEO" calibration facility using this method

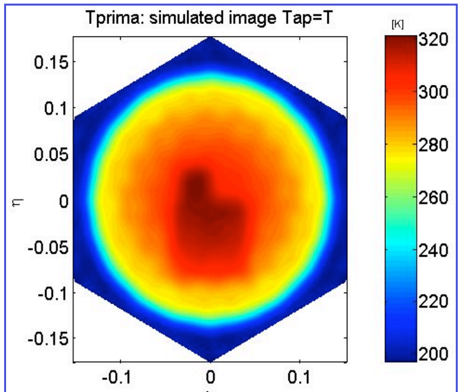
Quantitative-Calibration Facility

June 2006

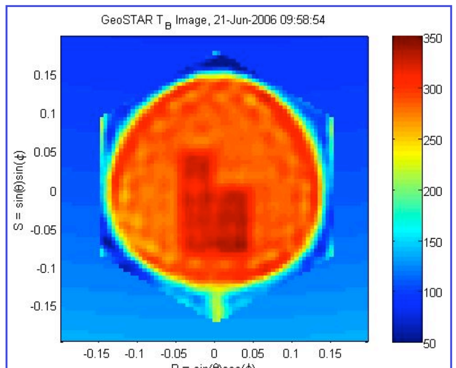






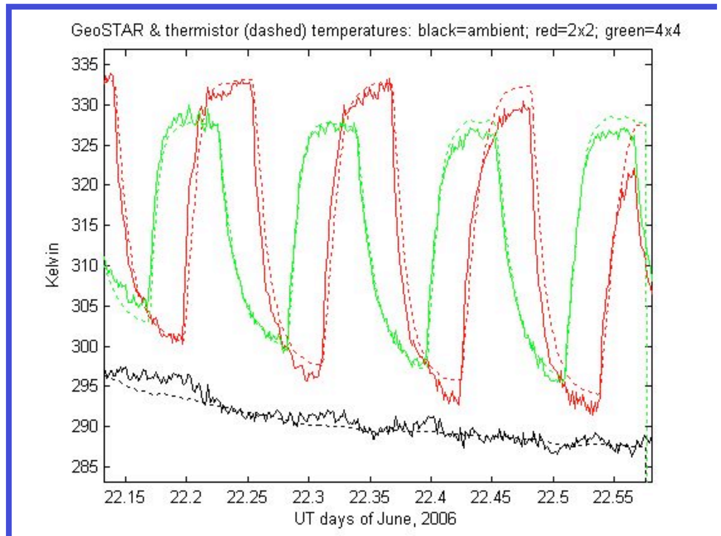


Raw synthesized image



Processed image†

† De-aliased, ant.patt. Corr; Not sidelobe-corrected



Retrieved vs. measured temperatures

Red: Large pad (4'x4' controlled)
Green: Small pad (2'x2' controlled)
Black: Main target (ambient)

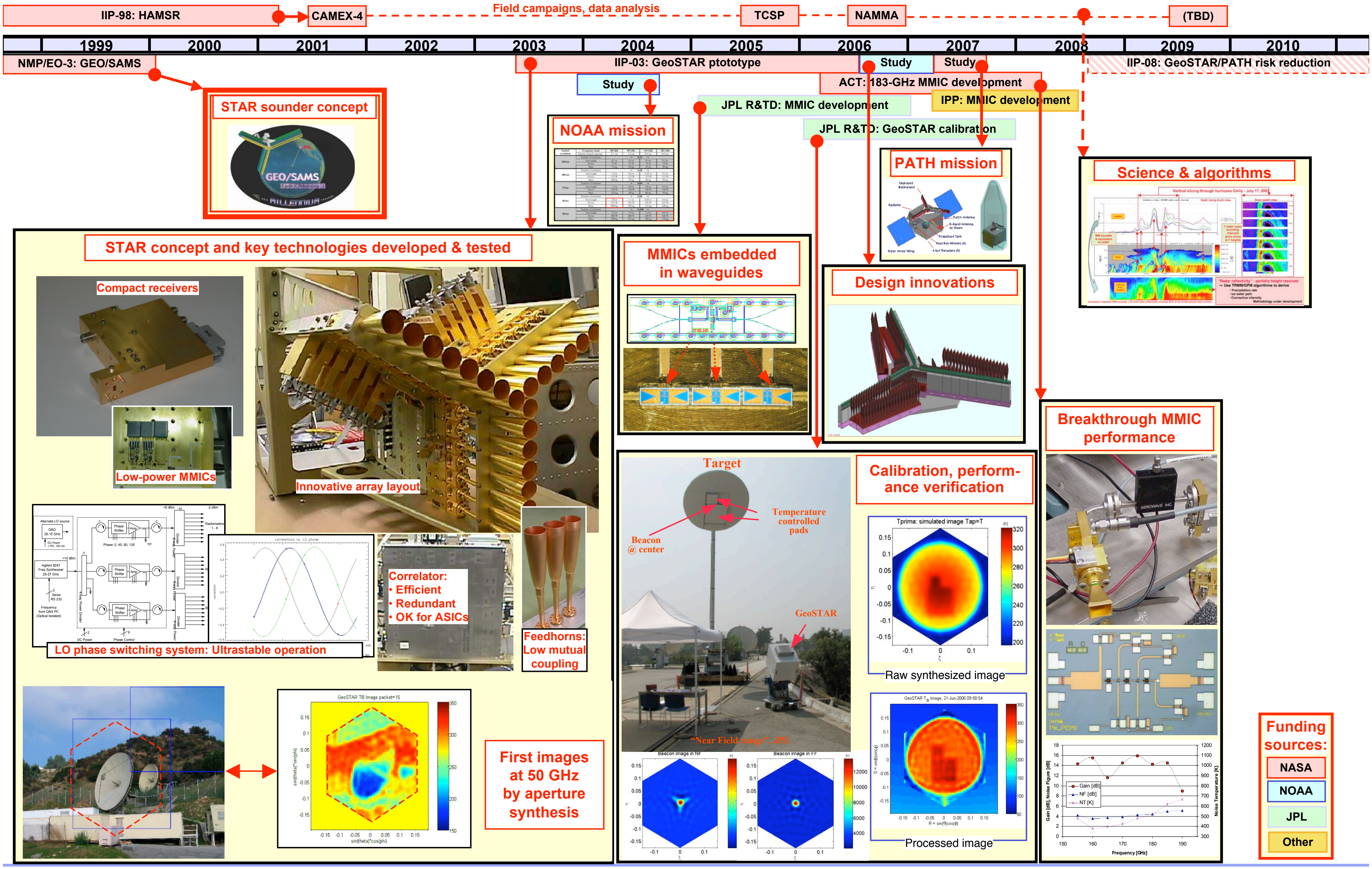
Solid: GeoSTAR retrieval
Dotted: Thermistor average

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

"Geosynchronous AMSU"

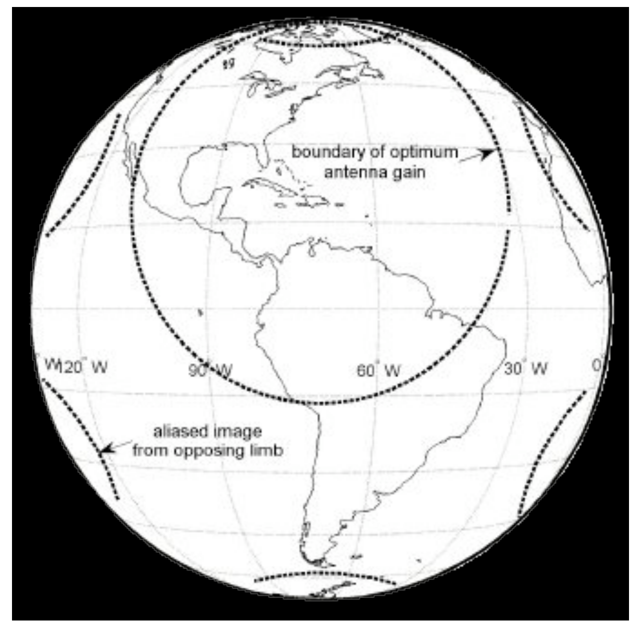
GeoSTAR Development History



Notional GeoSTAR Mission

- **Objective: Observe US hurricanes & severe storms**
  - Primary: Atlantic hurricanes
  - Secondary: CONUS severe storms; E. Pac. hurricanes
- **ROI focused near E. Carribbean**
  - Center @ 75°W, 20°N (permanently pitch GeoSTAR)
    - Can be pointed in other directions
  - 90+ % of visible disc is in alias-free region
    - Can be narrowed down (lower cost => risk mitigation)
  - Highest sensitivity in "circle" of radius 45°
    - Exploring antenna designs to maximize high-sensitivity region
- ***Alternative mission: "Pacific ENSO Observatory"***
- **Adequate sensitivity with GeoSTAR**
  - ~ 20 minutes "integration time" to reach 1/3 K for water vapor (183 GHz) in central part of ROI
    - T-band (50 GHz) is twice as sensitive/responsive
    - Exploring designs to improve these numbers
    - Exploring methods to increase temporal resolution
  - Focus is on high-value soundings in cloudy/unstable conditions
  - Bonus: Synergy with scatterometer & GOES-R sensors (ABI, GLM)

GeoSTAR = "staring" 2D imager-sounder:
- 60,000 pixels for T-sounding
- 240,000 pixels for H_2O-sounding
- Every 15 minutes
- Covering the entire visible disc



Science Mission Objectives

Mission Objectives	Measurement Requirements	Instrument Requirements	Mission Requirements
Observe and improve understanding and modeling of hurricanes, severe weather and related hydrology-cycle processes: • N. Atlantic hurricanes • CONUS severe storms • E. Pacific hurricanes • Tropical moisture transport • Oceanic and continental atmospheric processes • Diurnal cycles	**Functional** a) Soundings • T(z): 2 K/2 km • q(z): 20% / 2 km • L(z): 40% / 3 km • TPW: 10% • LWC: 20% b) SST • <0.5 K c) Precipitation • 25–50% **Temporal** • 15–30 minutes **Spatial** • T: <50 km/nadir • q: <25 km/nadir **Coverage** • Troposphere • Surface • All-weather • Continuous • ROI	**Spectral** AMSU ch. 3–8 AMSU ch. 17–20 **Radiometeric** <1K requirement <0.25 K goal **Antenna** 104/arm @ 50 GHz 192/arm @ 183 GHz ~4 λ spacing **Struct. stability** 0.5° @ center 1.5° @ periphery **Thermal** T_{op} ≈–30°C ΔT <1°C **Data bandwidth** 1 Mbps throughput	**Orbit** Geostationary, 75°W **Attitude** Pitch: 3.3°N Ctrl: 36 arcsec Stab: 1 arcsec/sec **Power** Range: 255–340 W **Thermal** 2 m^2 radiator + heat pipes **Operation** Continuous **Data** Latency: <15 min Rate: 1 Mbps avg Volume: 5 GB/day **Calibration** Ground transmitter

Data Products

Mature products :

Parameter	Horizontal	Vertical	Temporal	Accuracy
Tb (50 GHz)	50 km	(6 channels)	3 min per ch.	< 1/3 K
Tb (183 GHz)	25 km	(4 channels)	5 min per ch.	< 1/3 K
Temperature	50 km	2 km	20 min	1.5-2 K
Water vapor	25 km	2 km	20 min	25%
Liquid water	25 km	3 km	20 min	40%
Stability index	50 km	N/A	20 min	N/A
TPW	25 km	N/A	20 min	10%
LWC	25 km	N/A	20 min	20%
SST	100 km	N/A	1 hour	< 0.5 K

Evolving experimental products:

Parameter	Horizontal	Vertical	Temporal	Accuracy
Rain rate	25 km	N/A	20 min	2 mm/hr
Convect. intens.	25 km	N/A	20 min	N/A
IWC	25 km	N/A	20 min	30%
Wind vector	25 km	2 km	30 min	TBD

National Aeronautics and
Space Administration

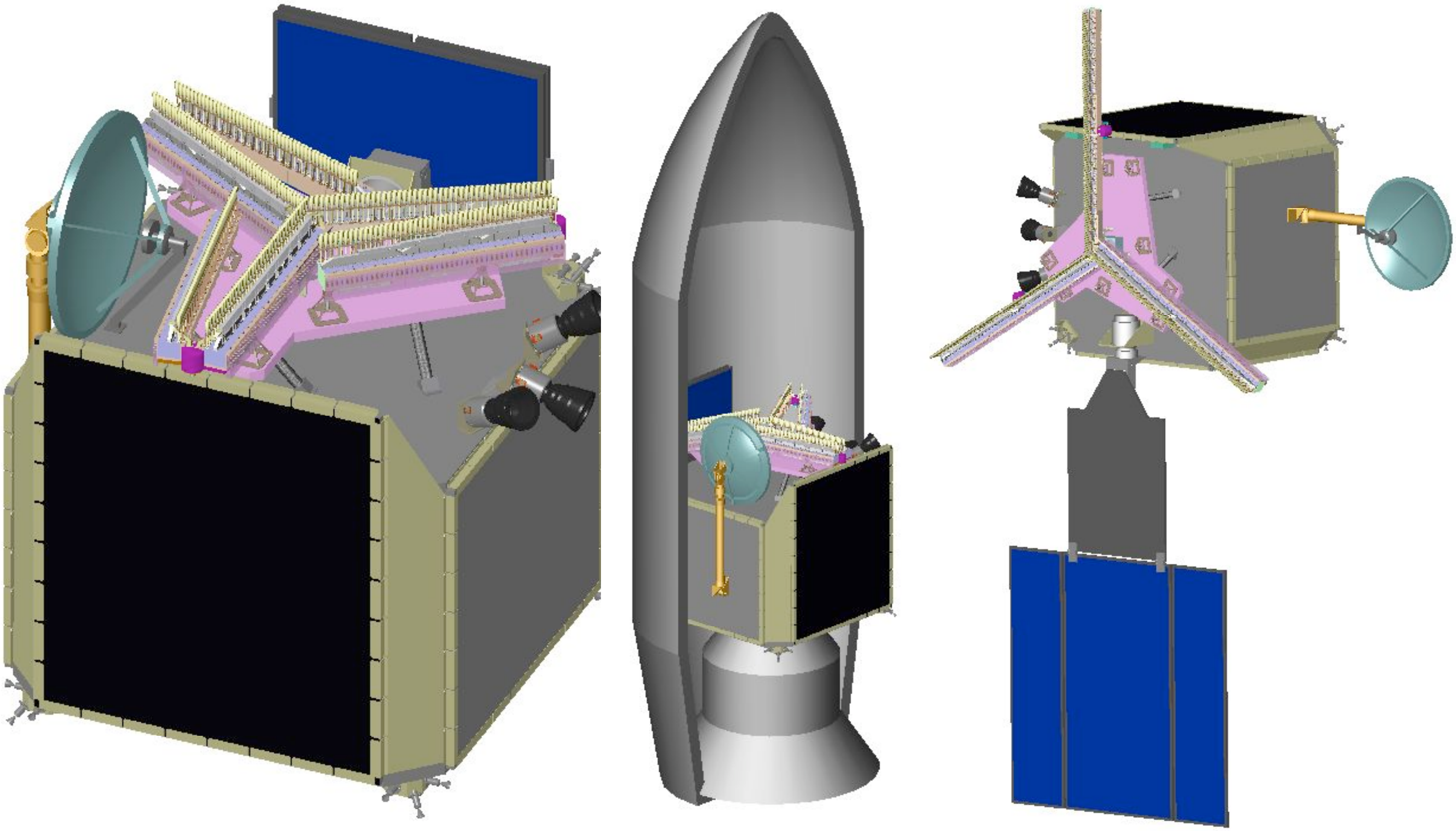
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Baseline Design

Instrument Type	Microwave sounder; Y-shaped antenna, each arm 2-m long. Currently TRL 5-6. Class C parts (redundancy is in design) Rectangular-shaped antenna arranged along S/C edges would facilitate easy integration with existing satellite system (MoO)
Frequencies	50 GHz & 183 GHz
Spatial Resolution	50 km (50 GHz) and 25 km (183 GHz) resolution
Sensitivity	Requirement: < 1 K; goal: 0.3 K
Temporal Resolution	Near-continuous, less than 15 min between downlinks. Dedicated ground station
Data Downlink	1 Mbps (average)
Mass	230 kg CBE (+ margin) → Can be reduced to ~200 kg
Power	340 W CBE (+ margin), 260 W + 80 W solar makeup heating
Pointing	Control to 36 arcsec; knowledge 10 arcsec; stability 1 arcsec/sec (all 3 sigma)
Thermal Control	–30°C ± 1°C (using flexible heat pipes + passive radiator)
Structural Alignment	0.1 mm receiver position accuracy; no mech. disturbances
Deployment Mechanism	Nominally to fit in Delta II fairing; once deployed, instrument has no moving parts

Baseline: Standalone NASA Mission

Note: Array arms can be remotely located from central electronics ⇒ Easy accommodation (e.g., GOES-R)



Array arms folded for launch **Stowed in Delta fairing** **Deployed on-orbit**

GOES-R Mission of Opportunity?

- Currently there is no HES payload on GOES-R and GOES-S (and maybe -T)
- HES slot is "kept open" as "Advanced Instrument" in S/C RFP
  210 kg + margin, 385 W + margin, large D/L bandwidth ← Ideal for GeoSTAR!
- NASA could develop and "demo" GeoSTAR on GOES-R/S
- A GEO MW sounder would have high value for NOAA
  - Solidly documented basis for need
  - Independent assessments conclude that GeoSTAR is the preferred design
  - Strong user community interest
- **Use "Advanced Instrument" slot to demo new capability as MoO**
  - MoO payload provided and managed by NASA
  - NOAA avoids programmatic riskz/complexity/cost of "operational" systems
  - NASA gains opportunity to demo new payload at low overall cost
  - NOAA obtains "advanced sounder" in lieu of HES and also reaches long-term MW goal
  - Perfect opportunity to demonstrate new "Research-to-Ops" paradigm
  - Effective cost sharing
    - NOAA provides platform and launch services, only minor additional cost: ≈ freebie @ minimal risk
    - NASA provides payload
    - Total cost is about 1/3 of full standalone mission cost
- **Requires negotiations & NASA-NOAA commitment/agreement**
  - Time is short
    - GOES-R (~2014 launch) requires 2009 pre-Phase-A start and 2010 Phase-A start
    - GOES-S (~2016 launch) requires 2010 pre-Phase-A start and 2011 Phase-A start

Flexibility: Instrument Options

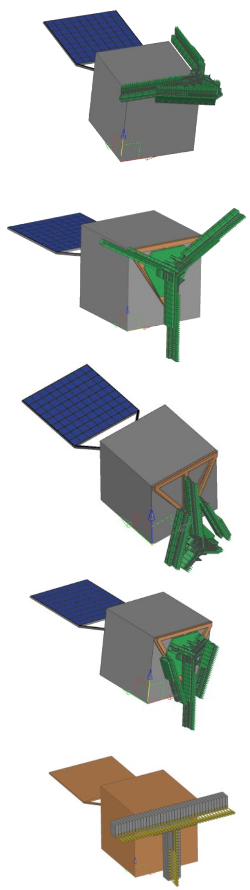
Note: Only baseline design has been studied in detail. Others are estimates.

- **Baseline design: dual array, 4-m aperture**
  - 50-GHz array: 50 km, 2-meter arms; 183-GHz array: 25 km, 1-meter arms
  - Full functionality
  - 230 kg, 340 W (Y-array) → 300 kg, 450 W (U-array)
- **Design option 1: dual array, 2-m aperture**
  - 118-GHz array instead of 50-GHz: 50 km, 1-meter arms
  - 90% functionality (no SST, marginal boundary layer T)
  - 200 kg, 290 W
- **Design option 2: dual array, 4-m aperture**
  - Same as baseline, but with a narrower FOV (Carribbean)
  - 90% functionality (no full disc coverage, focused on mature N. Atlantic hurricanes)
  - 200 kg, 340 W
- **Design option 3: single array, 2-m aperture**
  - Dual bands (118 & 183 GHz) with single array: 25 km @ 183 GHz, 38 km @ 118 GHz
  - 90% functionality (no SST, marginal boundary layer T - but: improved warm-core ΔT)
  - 190 kg, 350 W

Bottom line:

- ***The design is very flexible***
- ***There are several descope options that yield most of science***
- ***In general, the instrument can be sized to meet available resources***

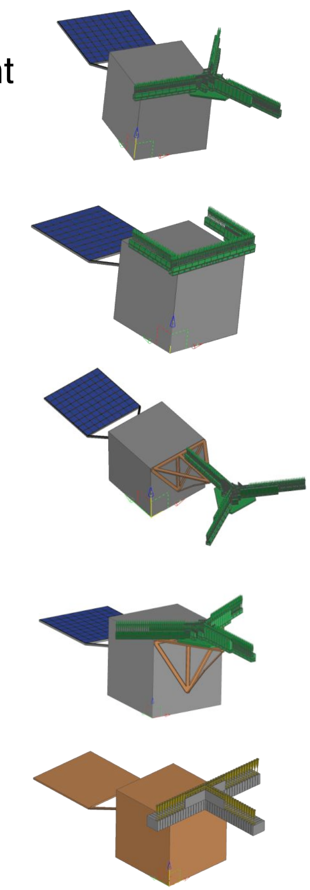
Flexibility: Accommodation Options



- **Baseline configuration: Integrated Y-array**
  - 2 collinear pairs of array arms (2 m & 1 m) - may be hinged at 1-m point
  - Integrated with central "hub" containing electronics & special circuitry
- **Separate array & electronics**
  - Y-array may be positioned remotely from electronics - connected w/cables
- **Other array configurations**
  - Rectangular "U": Antenna arms positioned along 3 S/C edges
  - Rectangular "T": Antenna arms positioned along 1 S/C edge + ⊥ arm
  - Distributed: Antenna arms distributed in "free" areas on nadir deck
- **Position on S/C**
  - Preferred: Corner; all 3 arms outside S/C envelope
  - Option: Edge; "T"-array + one arm deployed outside S/C envelope
  - Option: Any location; array deployed on boom fully outside S/C envelope

Bottom line:

- ***There are many feasible options***
- ***GeoSTAR is essentially easy to accommodate***
- ***We will design to fit available space & resources***



Stowed ← Example accommodation options → Deployed

Roadmap

- **Prototype: done! (2003-2006)**
  - Fully functional system completed under NASA IIP - now tested & characterized
- **Continuing risk reduction: 2006-2011**
  - Develop 183-GHz low-noise compact/lightweight multiple-receiver modules
  - Develop efficient radiometer assembly & testing approach
  - Migrate correlator design & low-power technology to rad-hard ASICs
  - *Second IIP effort now funded (NOAA to provide matching funds)*
- **Science and user assessment**
  - Forecast impact: OSSEs under development ← Seeking collaborations
  - Algorithm development; applications
- **Development of space version (PFM): ~2010-2014**
  - Start formulation phase in 2009-2010
  - Ready for integration in 2014
- **Joint NASA-NOAA demonstration mission: ~2014-2016?**
  - MoO on GOES-R/S?
  - Transition to quasi-operational mode after 1 year in research mode
- **Advocacy!**

Conclusions

- **Prototype development has been a tremendous success**
  - Inherently very stable design; Excellent performance
  - Measurements confirm system models and theory
  - *Breakthrough development!*
- **Technology risk is now manageable**
  - Prototype demo'd key technologies
  - There are fall-back solutions for all key elements
  - Remaining challenges are mostly "engineering risks"
    - Further risk reduction focused on efficient manufacture of large number of receivers
    - Design & fabrication of low-power correlator ASIC is a buy-down item, not a technology challenge
- **Science potential is tremendous - no other sensor can match this**
  - GeoSTAR is ideally suited for GEO
    - "Synoptic" sensor - continuous 2D imaging/sounding snapshots of Earth disc
    - Excellent match for sensitive high-resolution imagers: no moving parts, no interference
  - Soundings *in* hurricanes and severe storms
    - Water vapor, liquid water, ice water, precipitation - all vertically resolved
    - Can derive stability metrics (LI, CAPE, etc.), convective intensity
    - Now-casting: Detect sudden hurricane intensification/weakening
  - Major advances in models: Diurnal cycle of all 3 phases of H_2O fully resolved

Urgent need for this mission — Urgent need for advocacy


GEOSTAR
AMSU
in
GEO
NASA
COMING SOON:
SEE THIS IN
MICROWAVE!
The PATH SWG
Bjorn Lambrigtsen (JPL)
Bob Atlas (NOAA)
Ralf Bennartz (U. Wisc.)
Al Gasiewski (U. Colo.)
Jeff Hawkins (NRL)
Eugenia Kalnay (U. Md.)
Chris Kummerow (CSU)
T.N. Krishnamurti (FSU)
Chris Ruf (U. Mich.)
Chris Velden (U. Wisc.)
Duane Waliser (JPL)
Fuzhong Weng (NOAA)
Ramesh Kakar (NASA HQ)
The GeoSTAR team:
Todd Gaier,
Pekka Kangaslahti,
Alan Tanner - JPL
Chris Ruf - U. Michigan
Jeff Piepmeier - NASA/GSFC
This work was carried out at the
Jet Propulsion Laboratory,
California Institute of Technology
under a contract with the
National Aeronautics and Space Administration.